The importance of tree cover for water resources in semiarid West Africa

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Cover: Agroforestry parkland in Saponé (Burkina Faso, West Africa)
(photo: Aida Bargués Tobella)

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Abstract

The current paradigm in forest hydrology implies that an increase in tree cover always leads to reduced water yields as a result of increased interception and transpiration (ET) losses. This *trade-off theory*, in which more trees mean less water, has led to concerns that the establishment of trees in drylands may jeopardize scarce water resources. But in the seasonally dry tropics relevant studies are scarce, and few have explored the impact of intermediate tree densities on water yields in degraded soils, which greatly limits the applicability of the *trade-off theory* in this region.

Here, I propose an alternative *optimum tree cover theory* in which, under conditions typical of the seasonally dry tropics, groundwater recharge is maximized at an intermediate tree cover. At tree covers below this optimum, the gains from more trees on soil hydraulic properties exceed their additional ET losses, leading to increased groundwater recharge. The overall aim of this thesis is to test this hypothesis and to clarify the main processes influencing the relationship between tree cover and groundwater recharge. To do this, a number of measurements were taken in an agroforestry parkland in semiarid West Africa; these included soil infiltrability, soil water drainage, tree transpiration and degree of preferential flow, in combination with stable isotope data.

Results from this thesis show that deep soil water drainage was minimal near the tree stem, reached a maximum close to the canopy edge and from there decreased linearly with increasing distance to the nearest tree. This pattern is probably the result of a combination of increased ET losses next to the tree and reduced infiltrability and preferential flow with increasing distance from the nearest tree. The combined increase in infiltrability and degree of preferential flow close to trees allows for enhanced soil and groundwater recharge. Tree transpiration data were used in combination with the observed pattern in soil water drainage and data on tree water sources to model groundwater recharge as a function of tree cover. Modelling results confirm that groundwater recharge was maximized under intermediate tree cover irrespective of the scenarios considered. That trees do not always reduce water yields but can substantially improve them suggests new opportunities for tree protection and tree-based restoration in the seasonally dry tropics, benefitting hundreds of millions of people.

Keywords: Ecohydrology, Shea tree, *Vitellaria paradoxa*, Burkina Faso, Sahel

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Dedication

To Natxo and Nur, for all the love and support

Ce qui embellit le désert c'est qu'il cache un puits quelque part…
Antoine de Saint-Exupéry, Le Petit Prince (1943)

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I U. Ilstedt.*, A. Bargués Tobella*, H.R. Bazié, J. Bayala, E.Verbeeten, G. Nyberg, J. Sanou, L. Benegas, D. Murdiyarso, H. Laudon, D. Sheil, and A. Malmer (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Scientific Reports* 6:21930. DOI:10.1038/srep21930

II A. Bargués Tobella, H. Reese, A. Almaw, J. Bayala, A. Malmer, H. Laudon, and U. Ilstedt (2014). The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. *Water Resources Research* 50(4), 3342-3354. DOI:10.1002/2013WR015197

III A. Bargués Tobella, N.J. Hasselquist, H.R. Bazié, G. Nyberg, H. Laudon, J. Bayala, and U. Ilstedt (2016b). Strategies trees use to overcome seasonal water limitation in an agroforestry system in semiarid West Africa. *Under review in Ecohydrology.*

IV A. Bargués Tobella, N.J. Hasselquist, H. Laudon, U. Ilstedt. Soil water drainage in a future climate: interaction between tree cover and rain intensity in semiarid West Africa. *Manuscript*

* These authors contributed equally to paper I

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1 Introduction

1.1 Water, trees and forests

Water is an essential resource the availability of which underpins poverty reduction, social and economic development and environmental sustainability, and is thus key to realizing livelihood opportunities (WWAP, 2015). Water management contributes to four key dimensions of poverty reduction: enhanced livelihood security, reduced risks to health, reduced vulnerability and pro-poor economic growth (Soussan *et al.*, 2006). Today, more than 700 million people still lack access to adequate sources of drinking water; nearly half of them live in sub-Saharan Africa (WHO-UNICEF, 2014). Besides access to safe drinking water, the world's rural poor also lack access to reliable water supplies for agricultural production, which is usually their primary source of income (WWAP, 2015).

Fresh water storages and flows greatly affect ecosystems and livelihoods. Falkenmark (1995) created the concepts of *blue* and *green water* to distinguish between water found in streams, lakes and aquifers (*blue water*) and soil water available for plant transpiration and evaporation (*green water*), and to highlight the significance of the latter for food production in rainfed agriculture. *Blue water* is used for human consumption, irrigation, industries and other societal needs, and plays an important role in ecosystem functioning. Groundwater supplies drinking water to about half of the world's population and irrigation water to some 40% of the world's irrigated land, and it is a fundamental input in many segments of the industrial sector (Groundwater Governance, 2015). Moreover, groundwater stores sustain baseflows and dry season flows in streams and other aquatic ecosystems. If managed in a sustainable way, groundwater provides a reliable source of fresh water that can serve as a buffer in times of surface water scarcity (WWAP, 2015). Streamflow is also crucial. In many parts of the world, especially in seasonally dry environments, flow regime is more important than annual water yield for sustaining aquatic ecosystems and agricultural and industrial activities (Bruijnzeel, 1990). Dry season flows are vital for navigation, wildlife, rural communities, cattle, fish, and for irrigation systems that lack the technology to pump out groundwater (Aylward, 2005). In this sense, maintaining dry season flows is key to rural upland communities that rely on groundwater discharge during the dry season and who require a secure and perennial supply of water rather than increased total annual runoff (Sandström, 1998). *Green water* resources, on the other hand, sustain rainfed crops and all other non-agricultural terrestrial vegetation. Globally, *green water* predominates over *blue water* as a source of water for agriculture (Rost *et al.*, 2008) and it is therefore essential for food production. In sub-Saharan Africa alone, it is estimated that food production depends on *green water* resources by more than 95% (Alexandratos, 1995). Hence, the joint management of *blue* and *green* water is at the core of climate change adaptation strategies (WWAP, 2015).

Trees – both inside and outside forests – and forests provide a wide range of services, including provisioning, regulating, cultural and supporting services such as maintenance of biodiversity, erosion prevention and maintenance of soil fertility, provision of fibre, fuel and non-wood products, and carbon sequestration (Sinare & Gordon, 2015; Asbjornsen *et al.*, 2014; Chidumayo & Gumbo, 2010; Jindal *et al.*, 2008; Shvidenko *et al.*, 2005). Tree-based restoration and forestation (reforestation and afforestation) have been extensively promoted and adopted as a tool to restore or enhance the provision of such services and thus improve livelihoods. Some recent examples of large-scale tree-based forest and landscape restoration initiatives include the Bonn Challenge, a global target to bring 150 million hectares of land into restoration by 2020, and the New York Declaration on Forests that extends that challenge to 350 million hectares by 2030. Globally, Africa has been identified as having the greatest land area, over 715 million hectares, with forest and landscape restoration opportunities (Minnemeyer *et al.*, 2011). Specifically for Africa, there are two large-scale tree-based restoration initiatives: AFR100 (African Forest Landscape Restoration Initiative), a country-led effort to restore 100 million hectares of degraded and deforested landscapes by 2030, and the Great Green Wall for the Sahara and the Sahel Initiative, an African partnership to tackle desertification and land degradation. Both these initiatives recognize that mosaic restoration – mainly the establishment of trees on agricultural land, either through planting or managed natural regeneration – is the most widespread restoration opportunity in Africa.

Despite the many benefits of trees and forests, concerns have arisen that the establishment of trees in drylands may jeopardize already scarce water resources (Jackson *et al.*, 2005). These claims are based on the current scientific paradigm in forest hydrology that more trees lead to reduced streamflow and groundwater recharge (Brown *et al.*, 2005; Farley *et al.*, 2005;

Sahin & Hall, 1996; Bosch & Hewlett, 1982), but the scientific evidence behind this understanding has some important limitations. In this thesis, I would like to shed some light on the impacts of different degrees of tree cover on water resources in semiarid West Africa, paying special attention to soil and groundwater recharge. In few words, is the establishment of trees in this environment detrimental or beneficial for water resources?

1.2 The impacts of (de)forestation on groundwater recharge and streamflow

1.2.1 Contrasting views and perceptions

There is a widespread view among the general public, NGOs, government agencies and policy makers that forests maintain dry season flows and that forest removal leads to lowered groundwater levels, perennial streams becoming intermittent and springs drying up (Galudra & Sirait, 2009; Locatelli & Vignola, 2009; Calder *et al.*, 2004; Kaimowitz, 2004; Wilk, 2000; Sandström, 1998; Bruijnzeel, 1990; Hamilton & King, 1983). This view is based on the notion that forests act as giant sponges, soaking up water during wet periods and gradually releasing it during dry periods, thereby maintaining dry season flows (Malmer *et al.*, 2010; Hayward, 2005; Bruijnzeel, 2004; Wilk, 2000; Sandström, 1998; Bruijnzeel, 1990; Hamilton & King, 1983). In the light of this *sponge theory* and related ideas, many governments and NGOs promote forestation to restore springs, raise groundwater levels and increase dry season flows (Hayward, 2005; Calder *et al.*, 2004; Kaimowitz, 2004; Hamilton & King, 1983). Similarly, forest protection and conservation is promoted to maintain water supplies (Galudra & Sirait, 2009; Hayward, 2005). In many cases, tree-based restoration, forestation and forest conservation measures aimed at enhancing or maintaining water supply are promoted through financing mechanisms such as Payment for Ecosystem Services schemes (Ogden *et al.*, 2013; Locatelli & Vignola, 2009; Calder *et al.*, 2004). In turn, these measures are expected to improve the livelihoods of rural people through increased access to water (Ogden *et al.*, 2013; Calder *et al.*, 2004).

However, the popular view about the relationship between forests and water yields clashes with most of the available scientific evidence. Several reviews of paired-catchment studies and other catchment experiments looking at the impact of (de)forestation on water yields have been published (Brown *et al.*, 2005; Farley *et al.*, 2005; Scott *et al.*, 2005; Andreassian, 2004; Sahin & Hall, 1996; Bruijnzeel, 1990; Hamilton & King, 1983; Bosch & Hewlett, 1982). The general conclusion is that decreased forest cover leads to increased groundwater levels and streamflow, with the greatest increase usually occurring during the dry season or base flow conditions. Conversely, increased forest cover typically results in decreased groundwater levels and streamflow, with proportional reductions in dry season flow being typically larger than those in annual streamflow. The observed reduction in water yields with increasing forest cover, and vice versa, is generally attributed to the higher evapotranspiration losses from forests compared to shorter vegetation types such as grass, scrub or agricultural crops (Zhang *et al.*, 2001). This, in turn, is explained by the higher leaf area and canopy height of trees, and their deeper root system, which allows them to access deep soil water and even groundwater and thus maintain transpiration during periods with low water availability in the upper soil layers (van Dijk & Keenan, 2007; Scott *et al.*, 2005). On the basis of the available scientific evidence, a *trade-off theory*, in which more trees mean lower water yields, has become the dominant paradigm in forest hydrology.

Because of this paradigm, many forest hydrologists consider that the *sponge theory* and similar ideas are examples of the four Ms: "misinformation, misinterpretation, misunderstanding and myth" (Hamilton & King, 1983). This has raised concerns about bad policy making, as in many countries land use policies are formulated or advocated based on these Ms despite the fact that scientific evidence shows the opposite, and this could lead to undesirable or perverse outcomes (Locatelli & Vignola, 2009; Calder, 2007; Hayward, 2005; Kaimowitz, 2005; Calder *et al.*, 2004; Kaimowitz, 2004; Hamilton & King, 1983). Another field of concern has been in relation to the fact that the trade-offs or environmental co-effects of carbon sequestration projects, including reforestation and afforestation programmes, are usually not considered (Trabucco *et al.*, 2008; Farley *et al.*, 2005; Jackson *et al.*, 2005). It has been noted, for instance, that afforestation in dry regions could lead to shifts from perennial to intermittent flow regimes in streams or to the complete elimination of streamflow, and that reductions in runoff might cause or intensify water shortages (Farley *et al.*, 2005; Jackson *et al.*, 2005). Thus, in most countries land use policies are based on the notion that trees and forests are always good for water resources, while the potential trade-offs between forests and water are not acknowledged. However, there are some countries that have reformed their water legislation based on the *trade-off theory.* One of the best known examples worldwide is South Africa. According to the South African National Water Act (NWA) of 1998, forestry is classified as a 'stream flow reduction activity' (SFRA) and as such it must be licensed. Water use licenses are granted or declined based on consideration of all water use needs in the catchment and whether the proposed use is deemed 'beneficial' (Calder, 2005).

1.2.2 Limitations of the scientific evidence for the *trade-off theory*

Despite the apparent scientific consensus about the impacts of (de)forestation on water yields, it must be noted that the available scientific evidence for the *trade-off theory* is severely limited.

Geographical bias

One of the main limitations of the available scientific evidence for the *trade-off theory* is the strong bias of studies towards humid temperate areas, and the paucity of studies in the tropics in general and in the (semi)arid tropics in particular (Locatelli & Vignola, 2009; Hamilton & King, 1983). This under-representation of tropical areas in the scientific literature relating to forest and water yields is often a result of the high cost and time associated with catchment experiments (Bruijnzeel, 2004).

Hydrological processes, including runoff generation processes, may be quite different in the tropics than in temperate areas (Wohl *et al.*, 2012; Bonell, 1993). Of particular interest when dealing with streamflow, streamflow regime and groundwater recharge are those properties influencing the partitioning of rainfall into infiltration and infiltration-excess overland flow (or Hortonian overland flow), and those affecting sub-surface flow (or throughflow), which determine the pathways and the time needed for water to reach the stream channel. In this sense, it is important to highlight two aspects that can lead to differences in the hydrological response of tropical catchments compared to temperate ones: the characteristics of tropical soils and those of tropical rainfall. Tropical soils are, in general, fine textured and highly prone to degradation (Lal, 1983). When soil organic matter content is low, which is common in systems with low organic matter inputs and is linked to the rapid decomposition rates prevalent in the tropics (Solomon *et al.*, 2007a), soil aggregate stability is very poor. Structurally unstable soil aggregates break easily under the impact of raindrops, especially in the case of bare soils. This, in turn, can lead to the formation of surface crusts that diminish soil infiltrability (*i.e.,* infiltration capacity), thereby reducing the ability of soils to receive rainfall (Lal, 1983). Tropical rains, on the other hand, are typically short and intense and have a high energy load (Lal, 1983). The combination of soils with low infiltration capacities and the high intensity rainfall prevalent in the tropics results in a higher occurrence of infiltration-excess overland flow compared to the situation in humid temperate areas (Bonell, 1993).

Because of such differences, many authors conclude that drawing inferences and making generalizations based on evidence from temperate areas to tropical areas might be inappropriate and misleading (Ogden & Harmon, 2012; Wohl *et al.*, 2012; Malmer *et al.*, 2010; Bruijnzeel *et al.*, 2005). Moreover, given that the available scientific knowledge on tropical hydrology is limited and biased, it is extremely difficult to develop sound landscape policies or conceptual hydrological models for the tropics as a whole (Wohl *et al.*, 2012; Locatelli & Vignola, 2009).

Land cover vs. land use changes and the importance of considering soil degradation

A second limitation of the available scientific evidence for the *trade-off theory* is that most catchment experiments on the effect of forest removal on water yields involve forest cutting, but not conversion to a post-forest land use such as grazing or cropping, and many times not even logging (Brown *et al.*, 2005; Sandström, 1998; Bruijnzeel, 1990; Hamilton & King, 1983). Thus, what most experiments do is to study the impact of land cover change rather than the real-life situation in the tropics, where deforestation typically involves a change in land use. Making generalizations about the net effects of deforestation on water yields based on evidence from experiments in which land use conversions are not considered can be very problematic, as the effect of soil disturbance generally associated with post-forest land uses is not taken into account. Similarly, the majority of catchment experiments that study the impact of forestation on water yields are on non-degraded soils (Scott *et al.*, 2005). As a result, the observed changes in water yields in most (de)forestation studies only reflect a change in water use between contrasting vegetation types (Scott *et al.*, 2005; Bruijnzeel, 2004; Sandström, 1998).

Soil physical degradation typically encompasses a deterioration of soil structure, a decrease in soil aggregation, an increase in bulk density, and a reduction in soil hydraulic conductivity and soil infiltration and water storage capacities. Such soil degradation is widespread in the tropics, where it is frequently observed when forest is logged (Ziegler *et al.*, 2007; Malmer & Grip, 1990), grazed (Savadogo *et al.*, 2007), or converted to cropland (Nyberg *et al.*, 2012; Recha *et al.*, 2012; Abdelkadir & Yimer, 2011; Giertz & Diekkrüger, 2003; Islam & Weil, 2000; Mbagwu, 1997; Lal, 1996) or pasture (Muñoz-Villers *et al.*, 2015; Abdelkadir & Yimer, 2011; Zimmermann *et al.*, 2010; Geissen *et al.*, 2009; Zimmermann & Elsenbeer, 2008; Zimmermann *et al.*, 2006). Among the main causes of soil physical degradation following forest disturbance/conversion are soil compaction, mechanical destruction of the soil structure, increased exposure of soil to the impact of raindrops, decreased soil organic matter content and decreased soil faunal activity. The main consequence, on the other hand, is a change in the dominant runoff generation processes and pathways of water flow involving an increase in the occurrence of infiltration-excess and saturation overland flow and, in turn, an increase in storm runoff (Muñoz-Villers *et al.*, 2015; Ogden *et al.*, 2013; Recha *et al.*, 2012; Kashaigili, 2008; Bruijnzeel, 2004; Giertz & Diekkrüger, 2003) and erosion (Giertz *et al.*, 2005).

Bruijnzeel (Bruijnzeel, 2004; 1989) highlighted the fact that the increases in storm runoff resulting from forest disturbance/conversion may become so great as to seriously impair the recharging of soil and groundwater reserves that feed streams during the dry season. Thus, deforestation could theoretically result in diminished dry season flow if the increase in the amount of water leaving the area as stormflow due to decreased infiltration opportunities following forest conversion exceeds the gain in baseflows resulting from decreased evapotranspiration losses (Bruijnzeel, 2004; Bruijnzeel, 1989). Conversely, forestation of degraded land could restore dry season flow if the associated gains in infiltration opportunities (Ilstedt *et al.*, 2007) exceed the extra evapotranspiration losses from the new forest. In contrast, if soil hydraulic properties are not degraded following deforestation or rainfall intensities are so low that most rainfall can still infiltrate, dry season flow is expected to increase. Similarly, forestation of non-degraded land will probably lead to decreased dry season flow. In summary, according to the *infiltration trade-off hypothesis* (Bruijnzeel, 1989) the net effect of (de)forestation on dry season flow is the result of a balance between the associated changes in infiltration opportunities and evapotranspiration losses, and hence it can vary depending on the initial conditions and the nature of the changes involved (Fig. 1). The *infiltration trade-off hypothesis* may thus reconcile the two contrasting views on the impacts of (de)forestation on dry season flow (Bruijnzeel, 2004; Bruijnzeel, 1990; Bruijnzeel, 1989).

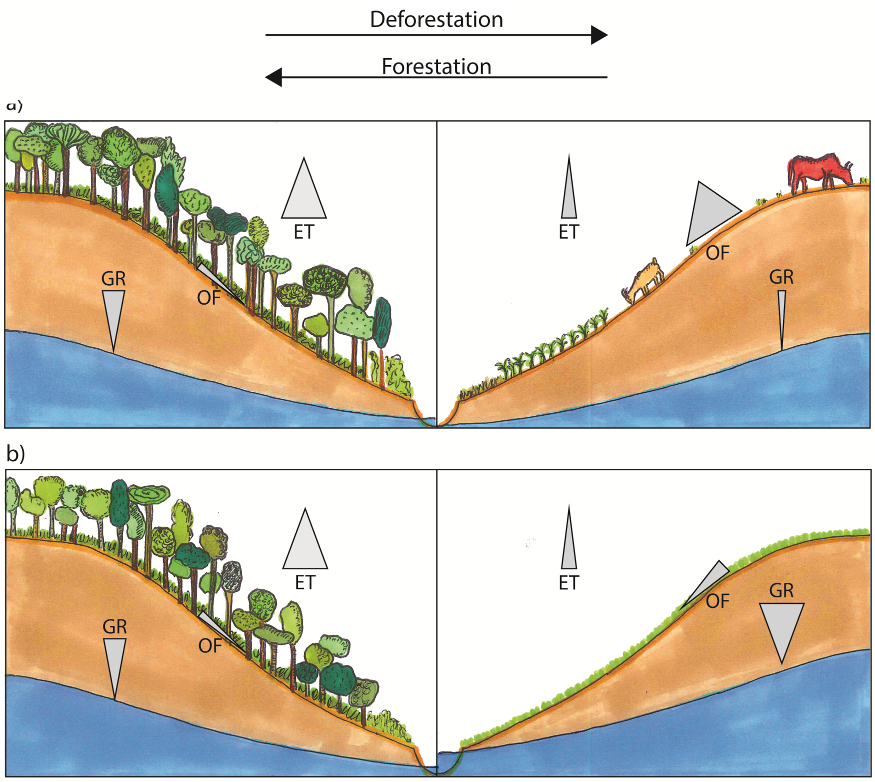

Figure 1. Overview of the *infiltration trade-off hypothesis* (Bruijnzeel, 1989), according to which the net impact of (de)forestation on dry season flow varies depending on the initial conditions and the nature of the changes involved. The grey arrows illustrate different hydrological flows (ET: evapotranspiration, *i.e.,* transpiration and interception; IF: soil infiltration; OF: overland flow; GR: groundwater recharge). a) Deforestation involving a change in land use associated with soil disturbance can lead to diminished dry season flow. Forestation of degraded land can enhance dry season flow if soil hydraulic properties are improved or restored. b) Deforestation involving only a change in land cover, without soil degradation, will lead to enhanced dry season flow. Forestation of non-degraded land will lead to diminished dry season flow.

In recent years, a number of studies providing evidence in support of the *infiltration trade-off hypothesis* have been published. In a study on the hydrological impacts of land use and land cover change in Tanzania, Kashaigili (2008) noted that dry season flow had declined during the study period, coinciding with an increase in the area of cultivated land at the expense of woodland. However, this trend could also be the result of the increase in water abstraction observed during the same period. Wilcox and Huang (2010) analysed the long-term trends of four catchments in Texas that had undergone a period of degradation followed by another of recovery involving increased woody vegetation and decreased grazing pressure. The authors found that the contributions of baseflow to total streamflow had increased following the recovery period even though annual rainfall did not change. Zhou *et al.* (2010) assessed the hydrological effects of a large-scale reforestation programme in southern China and concluded that forest recovery did not cause significant changes in annual river discharge, but that the water yield in the dry season had increased significantly. In a comparative catchment experiment in Panama, Ogden *et al.* (2013) observed that the runoff rate at the end of the dry season was 1-50% greater in a catchment covered by old secondary forest compared to that from a second catchment covered by a mosaic of land uses (including mixed-aged forest, pasture and subsistence agriculture). Moreover, during the dry season, the runoff from the forest catchment was greater than that from the mosaic catchment 80% of the time. In another comparative catchment experiment in India, Krishnaswamy *et al.* (2013) reported a higher frequency and longer duration of low flows in a catchment covered by natural forest compared to two other catchments under more disturbed land covers. Muñoz-Villers & McDonnell (2013) and Muñoz-Villers *et al.* (2015) compared the streamflow patterns of three neighbouring catchments in Mexico with contrasting land cover and land use: old-growth tropical montane cloud forest, naturally regenerating forest and heavily grazed pasture. They found that baseflow in the pasture catchment at the end of the dry season was about 35 to 70% lower compared to the mature and secondary forest catchments, respectively, and attributed this to a combination of more gentle slopes and lower soil infiltration capacities in the pasture catchment. Finally, Gebrehiwot *et al*. (2011) conducted a hydrological characterization of thirty-two catchments in the Blue Nile Basin, Ethiopia, and concluded that certain land use types such as dense wet forest, woodland and savannah grassland can enhance low flows, whereas more grazing land and bush land could exacerbate water shortages during the dry season.

Focus on certain tree species

A third relevant constraint of the available scientific evidence for the *trade-off theory* is that the great majority of studies have focused on the hydrological impact of only a few tree species. Reviews of catchment experiments by Bosch & Hewlett (1982) and Sahin & Hall (1996) divided the studies into four vegetation types: conifers, eucalypts, hardwoods and scrub; however, since most of the studies were conducted in temperate areas, the hardwood group only includes tree species from these environments, mainly oak, aspen and beech (Brown *et al.*, 2005). Studies on the impact of forestation are even more restricted in this sense. For example, the vast majority of studies included in the review by Farley *et al.* (2005) on the impact of afforestation on water yields involved either pines or eucalypts. This is also the case in the tropics. In their meta-analysis comparing water flows in tropical catchments under forest and non-forest lands, Locatelli & Vignola (2009) highlighted the fact that the studies involving planted forest only included eucalypts and pines, and that there were no studies available for other tree species, including native species. The lack of studies on the impacts of forestation with native tree species in the tropics is of great concern, especially when considering that research suggests that fast-growing exotic tree plantations use more water than native forest (Kagawa *et al.*, 2009; Licata *et al.*, 2008; Fritzsche *et al.*, 2006).

Paucity of long-term studies

A fourth limitation of the available scientific evidence for the *trade-off theory* is the paucity of long-term catchment studies. This is problematic given that both soil degradation–recovery processes and tree water use are time-dependant, and thus extrapolating the findings from short-term experiments to the long term can be misleading.

Changes in soil properties affecting runoff generation and groundwater recharge are related to time. For example, the recovery of soil infiltrability after forestation of severely degraded land can take many decades (Bonell *et al.*, 2010; Scott *et al.*, 2005). Likewise, the degradation of soil properties associated with forest conversion increases with time since conversion (Nyberg *et al.*, 2012; Recha *et al.*, 2012).

Tree water use studies indicate that stand transpiration rates decline with stand age (Delzon & Loustau, 2005; Vertessy *et al.*, 2001), which suggests that the negative impact of forestation on water yields observed in the short term could be neutralized in the long term. Evidence for this exists from a long-term study on the effects of afforestation with pine and eucalypt on streamflow in South Africa (Scott & Prinsloo, 2008). Findings from this study show that afforestation resulted in large reductions in streamflow, which increased with the age of the trees; however, as plantations matured, the trend in flow reduction was reversed, and streamflow tended towards pre-afforestation levels. Similarly, in a review of catchment studies on the impacts of afforestation on water yields, Farley *et al.* (2005) observed that low flows seemed to recover from a plantation age of 25 years. The main implication from such a recovery in streamflow as forest matures is that, if trees are grown on sufficiently long rotations, as might be the case in tree-based restoration activities, they may not have such a detrimental impact on water yields as expected from short-term studies (Scott & Prinsloo, 2008).

As noted by Brown *et al.* (2005), generalizations about changes in water yield as a result of changes in forest cover (Sahin & Hall, 1996; Bosch & Hewlett, 1982) are based on short-term catchment studies that only focused on the first couple of years following the change in forest cover. This is due to the fact that, in these experiments, forest was allowed to regenerate after forest harvesting and therefore, the effect of changes in forest cover had to be restricted to the data obtained in the period when the influence of the regrowth was not evident (Brown *et al.*, 2005). Since changes in soil properties and tree water use typically occur over a longer time scale, their effects cannot become apparent in such short-term experiments.

Not considering intermediate degrees of tree cover

A fifth limitation of the available scientific evidence for the *trade-off theory* is the lack of studies on the effects of intermediate levels of tree cover. Despite the fact that some of the catchment studies included in the reviews on the effect of (de)forestation on water yields have looked at partial changes in tree cover, these changes are at the catchment scale, and not at the stand scale (*i.e.,* a given percentage of the catchment area is treated).

The omission of any consideration of intermediate degrees of tree cover is surprising given the importance of this type of open vegetation in terms of extent, biodiversity (Manning *et al.*, 2009), and carbon storage (Saatchi *et al.*, 2011). In the global tropics, there are a total of 798 Mha of open and fragmented forests and 871 Mha of other wooded lands, an area slightly greater than that under closed forest (1229 Mha) (Shvidenko *et al.*, 2005). But open tree cover is even more common in certain regions. In tropical Africa, for example, open and fragmented forests and other wooded lands cover an area three times larger than that under closed forest (Shvidenko *et al.*, 2005). Trees outside forests, and in particular the inclusion of trees in farming systems (*i.e.,* agroforestry), need to be considered as well. Globally, it is estimated that about 40% of the area under agricultural land has a tree cover above 10% (Zomer *et al.*, 2014); Such tree cover makes an important contribution to the carbon pool on agricultural lands (Zomer *et al.*, 2016). In the global drylands, an estimated 13.5 billion trees are found outside forests, mostly in grasslands (50%) and croplands (39%) (FAO, 2016).

Forest hydrology, and more specifically catchment experiments looking at the effect of forest cover on water yields, have traditionally focused on studying the impact of closed forests, but not that of tree cover *per se*. Findings from such studies can be relevant for many purposes, for instance to predict the impacts of forestation on water yields. However, when it is not a forest that is established, but a number of trees forming an open tree cover, such as in the case of tree-based mosaic restoration activities, predictions based on these studies may be misleading. Therefore, it is highly relevant to study the impact of intermediate levels of canopy cover on water yields.

Other considerations about the available scientific evidence on the relationship between forests and water yields

In view of the limited number of studies of the impact of forest cover on water yields in the tropics, various authors have not only highlighted the need to conduct more paired-catchment experiments, but also to conduct process studies and physically-based model applications to assist in the full understanding of the results from paired-catchment experiments (which mainly represent a black-box approach) and to be able to extrapolate them to other areas (Scott *et al.*, 2005; Bruijnzeel, 2004; Bruijnzeel, 1990). In addition, more knowledge on changes in soil hydraulic properties and water use characteristics of tree species in the tropics is needed to build useful physically-based models (Bruijnzeel, 2004).

1.3 Tropical drylands

1.3.1 Characterization and the main challenges

Drylands, defined here as arid, semiarid and dry subhumid regions, cover around 35% of the global land area and are home to nearly 34% of the world's population (Safriel *et al.*, 2005). These regions, which correspond to the savannah and steppe ecosystems, are distinguished by fairly low ratios of annual rainfall to evaporative demand (aridity index values between 0.05 and 0.65 (UNEP, 1997)).The precipitation regime is characterized by a short rainy season followed by a long dry season, few and intense rainfall events unevenly distributed during the rainy season, and large spatial and inter-annual rainfall variability (Kalma & Franks, 2003).

Most soils in the semiarid tropics are characterized by their low structural stability (El-Swaify *et al.*, 1983; Hoogmoed, 1983), in particular when soil organic matter content is reduced (*e.g.* following deforestation), and are thereby highly sensitive and vulnerable to degradation. This is especially the case for Alfisols, which are known for their tendency to form seals and crusts at the surface. It is estimated that Alfisols and related soils with similar physical constraints occupy about 71% of the total land area in the semiarid tropics (El-Swaify *et al.*, 1984). Crust and seal formation is aggravated by the prevalent high rainfall intensities, and leads to problems with seedling emergence and to reduced soil infiltration and aeration, which in turn results in limited profile recharge, even when rains are moderate (El-Swaify *et al.*, 1983; Hoogmoed, 1983). The poor recharge of soil water, or *green water*, leads to the common occurrence of agricultural droughts. This, coupled with extreme spatiotemporal rainfall variability, high evaporative demand, recurrent floods and meteorological droughts, and the prevalence of surface runoff (infiltration-excess overland flow) and erosion, poses a challenge to reliable water supplies, food production and livelihood opportunities. It is not surprising, therefore, that people in tropical drylands lag significantly behind the rest of the world in terms of human well-being and development indicators (Falkenmark & Rockstrom, 2008; Rockström *et al.*, 2007; Safriel *et al.*, 2005; Falkenmark *et al.*, 1989).

1.3.2 The Sudano-Sahelian zone of West Africa

Climate

The Sudano-Sahelian zone, defined here as the area between the 200 mm and 1000 mm isohyets, stretches east–west across the African continent south of the Sahara desert and comprises two ecoclimatic regions, the Sahel and the Sudan (Fig. 2). The Sahel is a zone of transition between the desert and the more humid savannah to the south, and covers the area receiving between 200 and 600 mm mean annual rainfall. The Sudanian zone, on the other hand, is located between the Sahelian zone to the north and the Guinean zone to the south, and receives between 600 and 1000 mm mean annual rainfall (Nicholson, 1995; Le Houerou, 1980).

The climate of the Sudano-Sahelian zone of West Africa is characterized by high temperatures and high potential evapotranspiration as well as by strong spatial, inter- and intra-annual rainfall variability (Nicholson, 2013; Lebel *et al.*, 1997; Nicholson, 1995; Le Houerou, 1980). There is a single rainy season, which may occur between April and October, followed by a prolonged dry season. The seasonal cycle of rainfall is linked to the migration of the Intertropical Convergence Zone, which is the region where the dry north-easterly winds originating in the Sahara meet the humid south-westerly winds from the Atlantic (Nicholson, 2013; Nicholson, 1995). Both the duration of the rainy season and the amount of annual rainfall increase markedly from north to south (Nicholson, 1995; Le Houerou, 1980). Annual rainfall is not only concentrated in a relatively short rainy season, but a high proportion of it falls in the form of very intense rain events; for instance, observations across the region indicate that 25% of the annual rainfall falls at intensities above 30-90 mm/h (Table 1). Hence, rainfall is highly variable and both meteorological droughts and floods are common, placing great constraints on agricultural production and food security (Nicholson, 1995). The most recent, intense and persistent drought period in the region occurred in the early 1980s. Since then, rainfall in the Sahel has shown some degree of recovery, though it remained below the long-term mean in every year during the period between 1969 and 1997 (Nicholson, 2013; Nicholson, 1995).

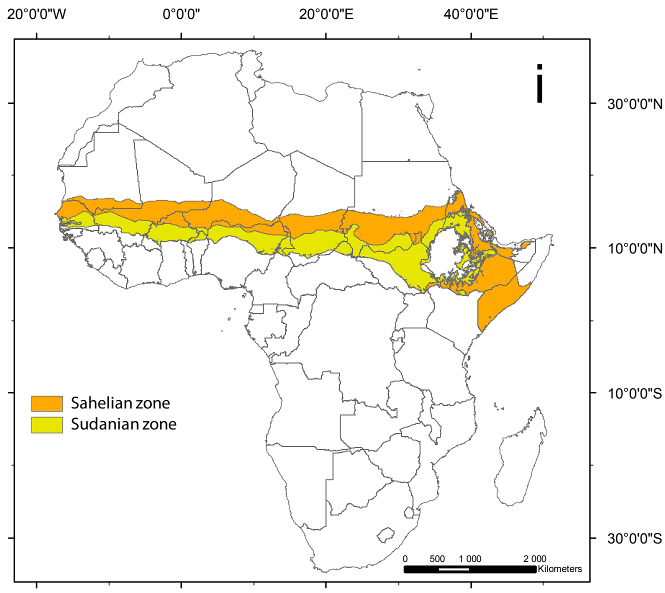

Figure 2. Location of the Sudano-Sahelian zone (adapted from the WorldClim dataset (Hijmans *et al.*, 2005))

Table 1. *Rainfall intensities (mm/h) in the Sudano-Sahelian zone of West Africa. The values represent percentiles based on the total annual rainfall amount.*

Location	25th percentile	50th percentile	75th percentile	Source
Niger	4-20	18-50	30-93	(Lebel *et al.*, 1997)
Burkina Faso				(Hoogmoed & Stroosnijder, 1996)
Fada N'Gourma	13	30	56	
Ouagadougou	13	30	55	
Dori	13	30	67	
Senegal				(Charreau, 1970)
Bambey	8.6	26.7	52.4	
Séfa	8.9	32.0	61.6	
Mali (*Niono*)	6-12	21-33	40-67	(Hoogmoed, 1981)
Niger (*Niamey*)	8-18	19-52	44-85	(Hoogmoed, 1981)

Vegetation, land cover and land use

The steep north–south gradient in mean annual rainfall and differences in soil characteristics give rise to a gradient in land cover and land use, ranging from sparse woody vegetation and grassland in the north, where land use is mostly pastoral, to savannah woodland, shrubland and cropland in the south (Sinare &

Gordon, 2015; Nicholson, 1995; Le Houerou, 1980). In general, vegetation height, proportion of woody species and vegetation ground cover increase along this north–south gradient (Nicholson, 1995).

In the Sudano-Sahelian zone of West Africa, agricultural production is mainly small-scale, subsistence-oriented and rainfed, and usually integrates the management of crops, trees and livestock (Powell *et al.*, 2004). The primary rainfed cereal crops are pearl millet, sorghum and maize, while among the most common legumes are cowpea and groundnut (Powell *et al.*, 2004). Cultivated soils are characterized by their inherently low fertility expressed through low levels of organic matter, total nitrogen, phosphorus and effective cation exchange capacity (Bationo & Mokwunye, 1991). This, added to the insufficient water supply linked to rainfall characteristics and soil physical constrains (Lal, 1991), strongly hinders crop production.

Scattered trees and shrubs are a common feature in the landscape of the Sudano-Sahelian zone of West Africa. In the so-called agroforestry parklands, mature multipurpose trees occur scattered on cultivated or recently fallowed fields (Boffa, 1999). The tree layer is the result of farmers' selection and retention of certain trees after clearing natural woodlands for cultivation, and the subsequent introduction and protection of trees in cultivated fields (Boffa, 1999; Bonkoungou *et al.*, 1994). The trees are deliberately associated with agricultural land and managed in combination with crops and livestock because of their specific use (Kessler, 1992). Parkland trees generate multiple benefits from provisioning ecosystem services – including nutritional diversity, medicinal uses, material assets, energy, sustenance of livestock, and income – and often have a positive impact on regulating ecosystem processes such as soil fertility (Sinare & Gordon, 2015). *Vitellaria paradoxa* C.F. Gaertn (Karité in French and Shea in English) is considered the main tree species in the parklands of West Africa (Bayala *et al.*, 2015; Lovett & Haq, 2000; Boffa, 1999; Breman & Kessler, 1995) and provides numerous non-timber products (Lovett & Haq, 2000), including shea butter, which is the main source of edible fat in the species distribution area (Lamien *et al.*, 1996). Other common and valued parkland tree species include *Parkia biglobosa* (Jacq.) G. Don (Néré in French), *Faidherbia albida* (Del.) A. Chev and *Adansonia digitata* L. (Baobab) (Boffa, 1999). Agroforestry parklands constitute the predominant farming system in the Sudano-Sahelian zone of West Africa, covering the majority of the cultivated area in this region and thereby contributing to the livelihoods of millions of people (Boffa, 1999; Kessler, 1992).

Trends in vegetation and tree cover: the re-greening of the Sahel

Woody vegetation in the Sudano-Sahelian zone was negatively affected by the droughts of the 1970s and 1980s. A combination of climate deterioration, drought-induced tree mortality and increased pressure of humans and livestock on trees resulted in a severe degradation of the tree cover compared to pre-drought levels, as shown by reports of reduced tree density and species richness (Gonzalez *et al.*, 2012; Vincke *et al.*, 2010; Hiernaux *et al.*, 2009; Maranz, 2009; Wezel & Lykke, 2006; Gonzalez, 2001).

In recent years, however, a number of remote-sensing studies have reported an increase in vegetation greenness (apparent in an increase in the Normalized Difference Vegetation Index, NDVI) across the Sudano-Sahelian zone since the droughts in the 1980s; this phenomenon is often referred to as *the re-greening of the Sahel* (Kaptué *et al.*, 2015; Dardel *et al.*, 2014; Anyamba & Tucker, 2005; Herrmann *et al.*, 2005; Olsson *et al.*, 2005). Despite the fact that this apparent recovery of the vegetation (or re-greening) is correlated with an increase in rainfall during the same period, the greening trend is not uniform and there are strong regional differences (Kaptué *et al.*, 2015), suggesting that rainfall is not the sole driver of the observed changes (Herrmann *et al.*, 2005; Olsson *et al.*, 2005). Some authors have hypothesized that a secondary causative factor operating on top of the climate trend is a human-induced change (Herrmann *et al.*, 2005); this hypothesis is based on widespread evidence of increased on-farm tree cover as a result of farmer restoration strategies, including farmer managed natural regeneration (FMNR) and soil and water conservation techniques (Haglund *et al.*, 2011; Sendzimir *et al.*, 2011; Reij *et al.*, 2009; Tougiani *et al.*, 2009; Reij *et al.*, 2005). However, some studies have shown that, in certain locations, satellite-sensed greening trends are mainly explained by an increase in the shrub cover, while there is an overall impoverishment of the woody cover in terms of species richness, loss of large trees and a shift towards more arid-tolerant species (Herrmann & Tappan, 2013).

The impact of changes in land use/land cover on water yield in the Sahel: the Sahelian paradox

Despite the reductions in rainfall experienced across the Sudano-Sahelian zone of West Africa from the early 1970s to the mid-1990s, increases in total annual streamflow and groundwater recharge have been observed. This paradoxical phenomenon is known as *the* S*ahelian paradox* (Sighomnou *et al.*, 2013) .

In an endorheic basin (*i.e.,* a closed drainage basin) in south-western Niger, Favreau *et al.* (2009) found that, despite a deficit in monsoonal rainfall, water tables had been rising continuously during recent decades. The authors linked this process to the clearing of savannah for cropping, which had led to the formation of impervious soil crusts. During the rainy season, these soil crusts enhanced the generation of surface runoff (infiltration-excess overland flow), which in turn eroded the soil creating gullies. Surface runoff was then concentrated in these gullies and in temporary ponds, leading to increased indirect groundwater recharge.

In the Nakambe river basin, in Burkina Faso, mean annual streamflow increased by 60% between 1955-1970 and 1972-1998 despite the fact that rainfall over the basin had decreased and the number of dams had increased; in this case, though, no long-term positive trends in groundwater levels were observed, which means that the increase in streamflow was not due to an increase in baseflow, but rather to an increase in stormflow. The authors attributed such an increase to the expansion of the cultivated area and bare soil, which had led to higher surface runoff coefficients (Mahe *et al.*, 2005). This is consistent with the observed increase in maximum daily discharges and peak flows in the basin (Mahe *et al.*, 2010; Mahe *et al.*, 2005), similar to the situation that has been reported for other Sahelian rivers (Amani & Nguetora, 2002).

1.3.3 The impact of scattered trees on their surrounding environment in tropical drylands

Scattered trees in tropical drylands greatly modify their surrounding environment. Concentrations of soil organic matter, organic carbon, total nitrogen and phosphorus are typically higher under isolated trees or tree clumps compared to the adjacent open areas, probably due to increased above- and below-ground litter inputs (Abdallah & Chaieb, 2012; Yadessa *et al.*, 2009; Bayala *et al.*, 2006; Kho *et al.*, 2001; Belsky *et al.*, 1993; Mordelet *et al.*, 1993; Isichei & Muoghalu, 1992; Belsky *et al.*, 1989). Higher levels of soil organic matter, in turn, improve soil structure and aggregate stability, which, added to the increased root and faunal activity in the vicinity of trees (Dunn, 2000), enhances soil porosity (Belsky *et al.*, 1993; Mordelet *et al.*, 1993; Belsky *et al.*, 1989). Macropores such as root and faunal channels, inter aggregate voids, cracks and fissures constitute pathways for the preferential flow of water through the vadose zone (Beven & Germann, 2013). In contrast to uniform or matrix flow, where water permeates the entire pore network of the soil matrix and moves downwards uniformly, preferential flow describes a non-uniform flow mechanism in which a fraction of the infiltrating water moves vertically thought the vadose zone along preferred pathways at much faster rates than the rest of the infiltrating water (Beven & Germann, 2013; Hendrickx & Flury, 2001). In drylands, preferential flow has been observed to occur via root and faunal channels both under shrubs and bush patches (Devitt & Smith, 2002; Bromley *et al.*, 1997). Moreover, it has been shown that in drylands, preferential flow contributes significantly to groundwater recharge, as water is allowed to bypass much of the soil matrix and thereby reach great depths rapidly (Mathieu & Bariac, 1996; Johnston, 1987a; Johnston, 1987b; Allison & Hughes, 1983).

Apart from its potential role in increasing preferential flow, higher macroporosity under trees, as well as improved soil physical properties in general, often leads to enhanced infiltrability (Joelsson, 2012; Hansson, 2006; Belsky *et al.*, 1993; Belsky *et al.*, 1989). A meta-analysis found that tree planting in the tropics, both in afforestation and agroforestry, improves soil infiltrability across a wide range of humidity levels (Ilstedt *et al.*, 2007). However, infiltrability can vary notably within the area under the canopy of trees. For instance, in a study on the effect of *Parkia biglobosa* and *Adansonia digitata* on soil infiltrability, Sanou *et al.* (2010) found that soil infiltrability was higher below the edge of tree crowns compared to the open areas, yet it decreased towards the trunk; this is probably a result of higher soil compaction under the canopies of trees, which are often used as shelter by people and animals. This is not always the trend for parkland trees, however. Joelsson (2012), for example, observed that infiltrability decreased with increasing distance from Shea trees, and did not find lower infiltrability values under the canopy of trees compared to the canopy edge.

Besides improving soil properties, isolated trees also modify the undercanopy microclimate: shading reduces both solar radiation and soil temperatures under trees compared to the adjacent open areas, while incident rainfall is diminished due to canopy interception (Abdallah & Chaieb, 2012; Belsky *et al.*, 1993; Belsky *et al.*, 1989). Moreover, soil evaporation losses can be significantly reduced beneath the canopy of trees compared to bare soil (Wallace *et al.*, 1999). In turn, reduced evaporation, coupled with improved soil infiltrability and water holding capacity, can lead to increased soil moisture under trees compared to the adjacent open areas (Abdallah & Chaieb, 2012; Sanou *et al.*, 2010).

Because of the afore-mentioned improvement in soil and microclimatic conditions under the canopies of trees, isolated trees in drylands have often been described as *islands of fertility* having a strong influence on community structure and ecosystem functioning (Rhoades, 1996).

1.3.4 The need for a better understanding of the impact of intermediate tree cover on groundwater recharge and dry season flows

The current scientific paradigm in forest hydrology, the *trade-off theory,* has severe limitations. In view of these limitations, it is currently not possible to draw any sound conclusions about the impact of intermediate tree cover on groundwater recharge and dry season flows in the tropics in general, and in the (semi)arid tropics in particular. This lack of knowledge is striking given the importance of landscapes with intermediate degrees of tree cover, but also given that tree-based forest and landscape restoration opportunities in drylands are mostly in the form of mosaic restoration rather than restoration into closed forests (Minnemeyer *et al.*, 2011).

Given that water scarcity adversely affects the livelihoods of millions of people in tropical drylands, it is of great importance to examine whether trees in these environments act merely as water consumers, as implied by the *trade-off theory,* or if, on the contrary, trees can actually improve water availability at the same time as providing a wide range of other services that contribute to livelihoods.

The *trade-off theory* implies that as tree cover increases, higher transpiration and interception losses will lead to reduced groundwater recharge. In this thesis, I propose an alternative theory, namely that under conditions typical of the seasonally dry tropics, groundwater recharge is maximized at an intermediate tree cover (Fig. 3). According to this *optimum tree cover theory,* at tree covers below the optimum more trees result in more groundwater recharge, as the benefits gained from more trees (*i.e.,* through enhanced infiltrability and preferential flow and reduced soil evaporation) outweigh the additional transpiration and interception losses from these trees. In contrast, above the optimum tree cover, increased transpiration and interception losses dominate any benefits trees might have on groundwater recharge, and so more trees lead to less groundwater recharge.

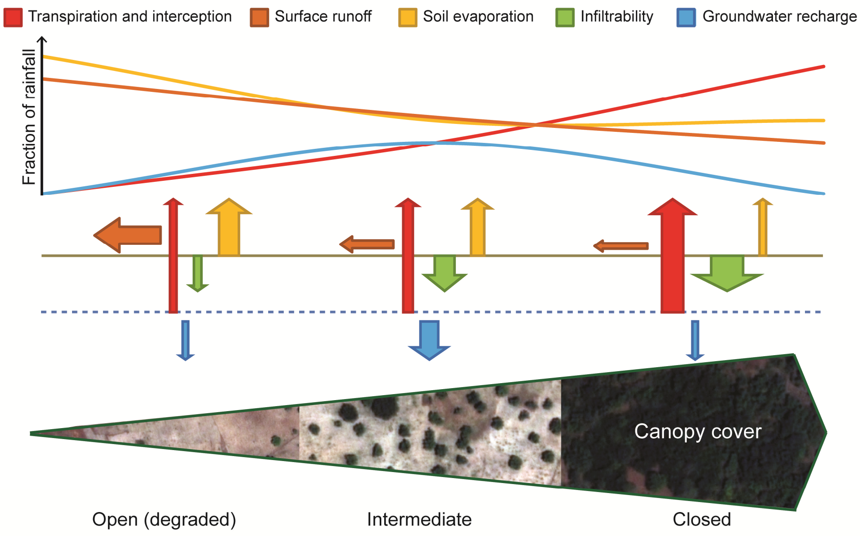

Figure 3. Overview of the *optimum tree cover theory*, in which groundwater recharge is maximized at an intermediate level of tree cover. When trees are not present, surface runoff (infiltration-excess overland flow) and soil evaporation losses are very high, leading to low groundwater recharge despite low transpiration and interception losses. Under a closed tree cover, transpiration and interception losses are so high that they exceed the gains conferred by trees through enhanced infiltrability and reduced soil evaporation, again leading to low groundwater recharge.

2 Objectives

The overall aim of this thesis is to gain a better understanding of the impact of tree cover on water resources, and more specifically on groundwater recharge, in the seasonally dry tropics by studying an agroforestry parkland in semiarid Burkina Faso, West Africa.

The specific objectives of each paper are:

- I- To evaluate the *optimum tree cover theory* and test the hypothesis that groundwater recharge is maximized at an intermediate level of tree cover (Fig. 3).
- II- To investigate the effect of trees and associated termite mounds on soil infiltrability and preferential flow
- III- To determine the relative contribution of different water sources to Shea tree water uptake and explore how seasonality and tree size affect where trees access water.
- IV- To evaluate how tree cover affects soil water dynamics in relation to rainfall intensity

The papers look at a combination of processes in order to improve our mechanistic understanding of the relationship between tree cover and groundwater recharge (Fig. 4):

- Soil infiltrability (paper II and indirectly in paper I)
- Mechanisms of water flow in the vadose zone, *i.e.,* degree of matrix vs. preferential flow (papers II and IV and indirectly in paper I)
- Tree water use, including transpiration rates (paper I) and tree water sources (paper III)
- Soil evaporation (paper IV and indirectly in paper I)
- Interception by trees (indirectly addressed in paper I)
- Infiltration-excess overland flow (indirectly addressed in papers II and IV)

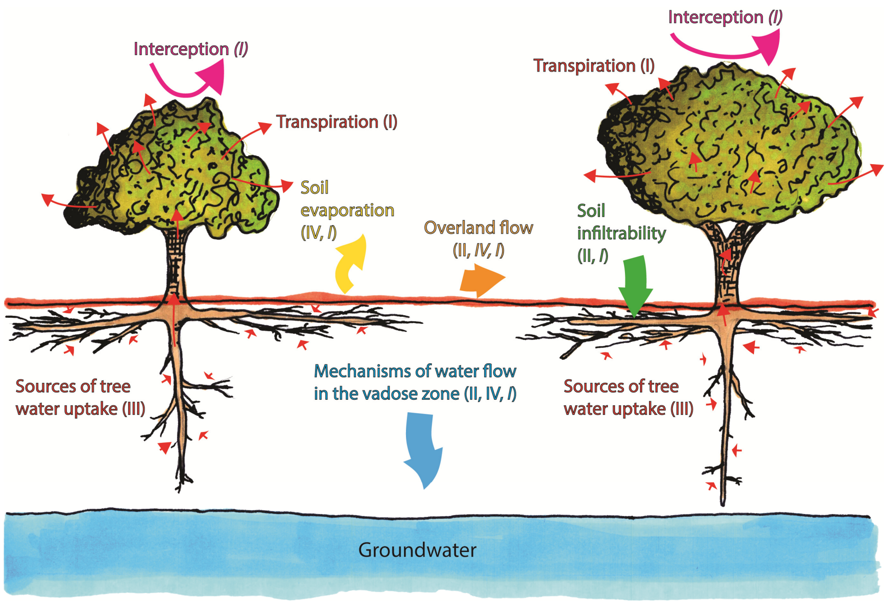

Figure 4. Overview of some of the processes affecting the relationship between tree cover and groundwater recharge in conditions typical of the semiarid tropics. Roman numerals indicate the specific paper(s) in which the process is addressed.

3 Material and Methods

3.1 Study area

Papers I-IV are all based on data collected in the agroforestry parklands of Saponé, a rural municipality located 30 km south of Ouagadougou, in central Burkina Faso, West Africa (12° 04’ 48’’ N, 1° 34’ 00’’ W) (Fig. 5, Fig. 6). The study area, which covers *ca.* 130 ha, is located on a peneplain at 310 to 325 m a.s.l. Mean annual temperature (1952-2014) at Ouagadougou (the nearest meteorological station) is about 28 °C, mean annual precipitation is 790 mm/year, ranging between 570 and 1189 mm/year, and mean annual potential evapotranspiration (1974-2003) is 1900 mm/year (Direction de la Météorologie du Burkina Faso). The ratio of mean annual precipitation to mean annual potential evapotranspiration, or aridity index, is 0.38 (1974-2003), and thus the climate is classified as semiarid (UNEP, 1992). There is a single rainy season from April to October, with around 70% of the total annual rainfall falling between July and September, and a pronounced dry season from November to March.

The soils of the study area have been classified as sols ferrugineux tropicaux lessivés (CPCS, 1967), corresponding to Ferric Lixisols (FAO-ISRIC-ISSS, 1998) or Alfisols (Soil Survey Staff, 2006). They have sandy clay and sandy loam textures and low nutrient content (Jonsson *et al.*, 1999). Laterite appears typically at a depth of between 50 and 150 cm.

The vegetation overstory consists of an open layer of scattered trees dominated by *Vitellaria paradoxa* C.F.Gaertn. (commonly known as Karité in French and Shea in English), which is considered the dominant parkland tree species in semiarid West Africa (Bayala *et al.*, 2015; Lovett & Haq, 2000; Boffa, 1999; Breman & Kessler, 1995). Other tree species present in the parkland are *Parkia biglobosa* (Jacq.) G. Don, *Azadirachta indica* A. Juss., *Diospyros mespiliformis* Hochst. ex A. DC., *Adansonia digitata* L., *Acacia* *nilotica* (L.) Delile, *Ficus gnaphalocarpa* (Miq.) Steud. ex Miq., *Khaya senegalensis* (Desv.) A. Juss., *Lannea microcarpa* Engl. & K. Krause, *Sclerocarya birrea* (A. Rich.) Hochst., *Tamarindus indica* L. and *Terminalia laxiflora* Engl. Average tree density is about 20 trees/ha, which is within the range of reported tree densities for West African agrofrorestry parklands (Boffa, 1999). Annual crops such as millet, sorghum, peanut and cowpea are cultivated under and among scattered trees. The cropping season starts between May and July, depending on the onset of the rainy season, and harvesting generally takes place in November. Fields are typically left fallowed for 3-5 years, and livestock is allowed to graze in the fallows and in the agricultural fields once they have been harvested.

Termite mounds are abundant in the study area, and are typically located under trees. The few mounds that do occur in the open areas tend to be smaller than the ones found under trees.

3.2 Experimental designs

3.2.1 Papers I and IV

The sampling for papers I and IV was designed to estimate changes in soil water drainage (Healy, 2010; also referred to as percolation) and groundwater recharge as a function of tree proximity and tree density. In order to span a range of tree densities, two classes of sampling locations were selected: large and small open areas among tree canopies (Fig. 5b; for information about replicates see Table 2). The selected large and small open areas had a radius of 22-30 m and 6-13 m, respectively. In each sampling location, two soil pits were excavated, one at the centre of the open area and a second one under a tree (Fig. 5b, Fig. 6f). Soil water drainage was collected using passive capillary fibreglass wick lysimeters at depths of 50 cm and 150 cm in one sidewall of the soil pit located at the centre of the open area, and in two opposite sidewalls of the soil pit located under a tree, resulting in a total of six measurement points per sampling location. Soil water was collected on a daily basis during the rainy seasons in 2008, 2009 and 2010 in six, eight and nine sampling locations respectively (Table 2), corresponding to 36, 44 and 50 measurement points (during 2008, one soil pit under a tree was destroyed due to heavy rains and these four measurement points were not included in the following years). In addition, rainfall was collected in a rain gauge located near the centre of each open area.

As well as soil water drainage and rainfall, tree water use was also measured. In each open area, three healthy and not recently pruned Shea trees were selected for sap flow measurements.

Table 2. *Number of sampling locations (total, large open areas and small open areas) for each year*

Year	Sampling location		
	Total	Large	Small
2008	6	3	3
2009	8	4	4
2010	9	4	5

3.2.2 Paper II

The sampling for paper II was designed to assess the effect of tree cover, individual trees and termite mounds associated with trees on soil infiltrability and preferential flow. Like the experimental design for the work described in papers I and IV, two classes of open areas were selected to span a range of tree densities: large and small. Each open area included a transect consisting of three sampling positions (Fig. 5c): (i) a Shea tree associated with a termite mound, (ii) a single Shea tree on the opposite side of the open area compared to (i), and (iii) the centre of the open area. In each sampling position, one rainfall simulation and one dye infiltration experiment were carried out. A total of six transects were selected, three corresponding to large (distance between the two transect trees ranged between 77 and 127 m) and three to small (between 20 and 30 m) open areas, resulting in a total of 18 rainfall simulations and dye infiltration experiments.

3.2.3 Paper III

In paper III, soil, plant xylem and groundwater samples were collected during both the dry and the wet season for isotopic analyses; the objective was to determine the relative contribution of different water sources to Shea tree water uptake. Ten healthy, not recently pruned Shea trees spanning a range of tree sizes were selected for xylem sampling. One soil pit was excavated under the canopy edge of each individual tree in order to collect soil samples down to 110 cm depth. Deeper soil samples and groundwater were collected from a well located within the study site.

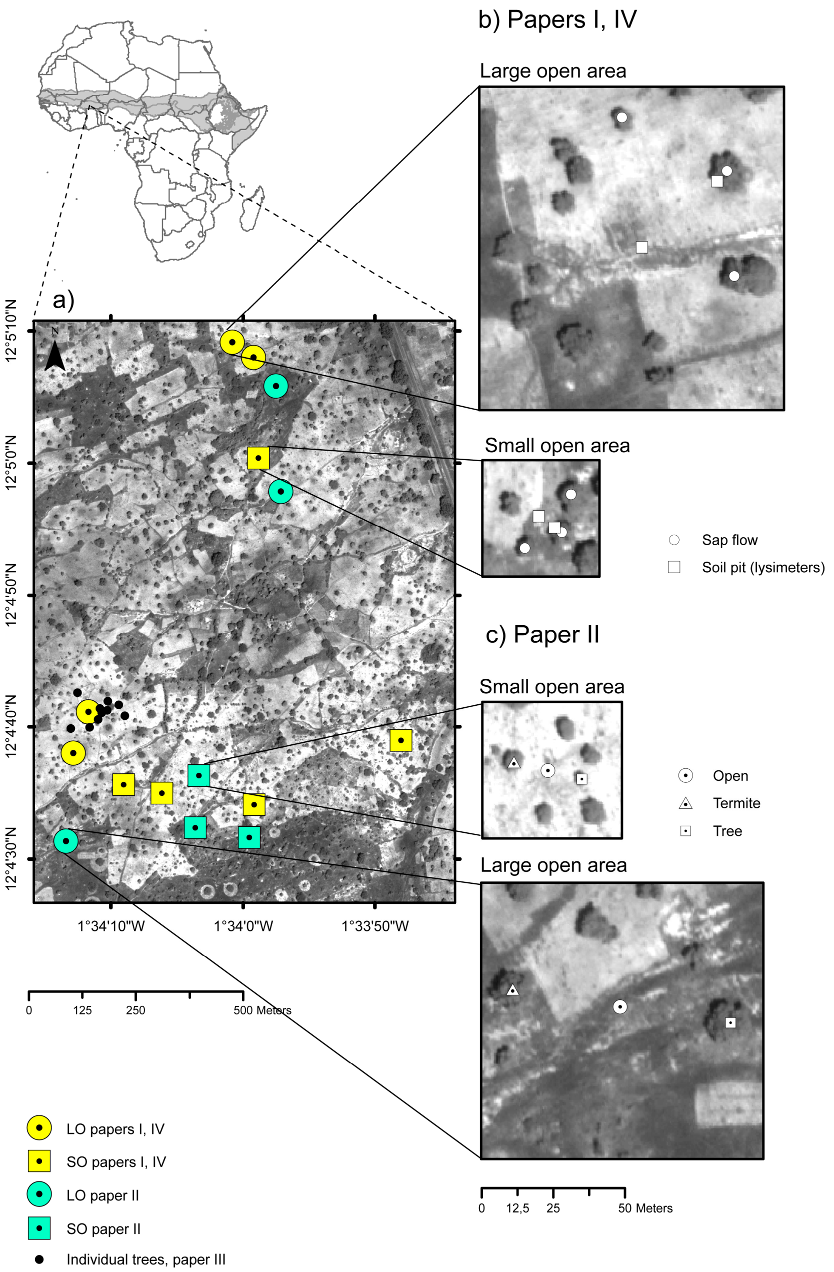

Figure 5. a) Overview of the study area (Panchromatic WorldView-2 satellite image from 21 October 2012), which is located in the municipality of Saponé, in central Burkina Faso, West Africa. Sampling locations for the work described in the different papers are also shown: large and small open areas (LO, SO) for papers I (and IV) and II, and individual Shea trees sampled for paper III. b) In each of the open areas or sampling locations selected for papers I and IV, soil pits

were located both at the centre of the open area and under a tree. Soil water drainage was collected with lysimeters located at depths of 50 cm and 150 cm in one of the sidewalls of the soil pit located at the centre of the open area, and in two opposite sidewalls in the pit located under a tree. Sap flow was measured in three Shea trees per open area. c) Each of the open areas in paper II constituted a transect consisting of three sampling positions: tree (under a single Shea tree), open (centre of the open area); termite (under a Shea tree associated with a termite mound).

3.3 Field measurements and sampling

3.3.1 Soil water drainage and rainfall measurements (papers I and IV)

Rainfall was measured in 2-L gauges mounted at a height of 1.5 m near the centre of each open area.

Soil water drainage was collected using passive capillary fibreglass wick lysimeters with a collection surface of 30 × 40 cm adapted from those described by Zhu *et al.* (2002) (Fig. 6g). Passive capillary fibreglass wick lysimeters extract mobile soil water via fibreglass wicks that produce a hanging water column that exerts suction on the soil above the lysimeter (Holder *et al.*, 1991). The vertical distance between the collection surface and the end of the wick was about 50 cm, which thus generated a tension up to 50 cm of water (4.9 kPa) on the soil. Drainage collection efficiencies of passive capillary fibreglass wick lysimeters are greater than those of normal zero-tension pan lysimeters, and can approach 100% (Zhu *et al.*, 2002).

Two cavities were dug 50 cm into the sidewalls of the soil pits, one at 50 cm beneath the soil surface and a second at 150 cm (Fig 6h). The lysimeter surface was then placed against the ceiling of the cavity. Soil pits were covered with an unpainted galvanized iron sheet to reduce evaporation and avoid direct precipitation.

Rainfall and lysimeter water were collected daily during the rainy seasons in 2008, 2009 and 2010. After recording the water volumes, soil water samples were collected to conduct isotopic analyses. Airtight vials were completely filled with water, sealed with parafilm and stored in a refrigerator (4 °C).

Some lysimeters malfunctioned during use: three out of a total of 36 in 2008, two out of 48 in 2009 and one out of 54 in 2010, most likely due to poor contact between the lysimeter collection surface and the soil matrix resulting from flawed installation, erosion, or disturbance by animals. Readings from these lysimeters were exluded from the data set.

3.3.2 Sap flow measurements (paper I)

Sap flow was measured using the heat ratio method (HRM) (Burgess *et al.*, 2001) in a total of 27 Shea trees, corresponding to nine sampling locations, in both the rainy season and the dry season over the period July 2008 – December

2010. On each Shea tree, four HRM30 sensors (ICT International, Armidale, Australia) were installed at a height of 1.30 m at the cardinal points: East, West, North and South. Each sensor was 35 mm long and contained three probes: a heater probe and two temperature probes installed equidistantly upstream and downstream from the heater probe (Fig. 6i). Each temperature probe, in turn, contained two thermocouples located at 7.5 and 22.5 mm. Heat pulse velocity was calculated according to Marshall (1958), and subsequently corrected for potential errors arising from probe misalignment and wounding following Burgess *et al.* (2001). The resulting corrected heat pulse velocity values were then converted into sap velocity according to Barrett *et al.* (1995). Volumetric sap flow was calculated for each monitored tree from sap velocity and measured sapwood area according to Burgess *et al.* (2001). Finally, the tree's hourly transpiration rate was calculated by averaging the sap flow values from the four sensors installed in each tree, and daily transpiration was estimated by combining the hourly transpiration rates. Sap flow was measured simultaneously on three trees per sampling location for a period of 10-50 days, after which the instrument was moved to another sampling location.

3.3.3 Rainfall simulations and dye infiltration experiments (paper II)

In each sampling position, one rainfall simulation was carried out using a drip-type Amsterdam rainfall simulator adapted from the one described by Bowyer-Bower & Burt (1989) (Fig. 6j,k). Simulations were performed over a 106 × 55 cm runoff collection plot at an intensity of 45 mm/h for at least 1 h or until steady state infiltrability (Hillel, 2004) was reached. Surface runoff (infiltration-excess overland flow) volume was recorded manually every two minutes and the infiltration rate was subsequently obtained by subtracting the runoff rate from the rainfall intensity.

Following each rainfall simulation, a dye infiltration experiment was carried out to visualize the flow pattern of the infiltrated water. Fifty litres of Brilliant Blue FCF (C.I.42090) dye solution at a concentration of 4 g/L (Flury & Fluhler, 1995) were added into the runoff collection plot and allowed to infiltrate. One hour after the solution had infiltrated, six parallel vertical 50 × 50 cm soil profiles were photographed (Fig. 6m,n).

3.3.4 Collection of soil, plant xylem and groundwater samples (paper III)

Soil, plant xylem and groundwater samples were collected for isotopic analyses during both the dry and the wet seasons. Two xylem samples were extracted from the trunk of each of the ten individual trees using an increment borer at a height of 1.3 m. One soil pit was excavated down to a depth of 110 cm under the canopy edge of each individual tree, and one soil sample was collected from the sidewalls of each pit at depth increments of 0-10 cm, 10-30 cm, 30-50 cm, 50-70 cm, 70-90 cm and 90-110 cm. Deeper soil samples were collected from a well at 125 cm, 150 cm, 200 cm and thereafter every meter until the groundwater table was reached. Two soil samples were collected at each depth from two opposite sidewalls of the well 20 cm (at least) into the sidewall to prevent any effects of evaporative enrichment. Xylem and soil samples were placed in airtight vials, sealed with parafilm and stored frozen (-20 °C). Two groundwater samples were collected from the well using airtight glass vials that were filled completely, sealed with parafilm and stored in the refrigerator (4 °C).

3.4 Laboratory analyses

3.4.1 Water extraction for isotopic analyses (paper III)

In order to perform water isotopic analyses, water was extracted from soil and plant xylem samples using a cryogenic vacuum distillation line (West *et al.*, 2006; Ehleringer *et al.*, 2000). The extractions were carried out for 90 minutes at a temperature of 100 °C. Soil gravimetric water content was determined for each sample by comparing soil mass before and after water extraction.

3.4.2 Isotopic analyses (papers III and IV)

Water samples – groundwater and water extracted from soil and plant material (paper III) and a subset of soil water drainage samples (paper IV) – were simultaneously analysed for δ^{18}O and δ^{2}H by isotope ratio infrared spectroscopy (IRIS) using a Picarro L2130-i Cavity Ring-Down Spectroscopy (CRDS) analyser coupled to an A0211 high-precision vaporization module (Picarro Inc., Santa Clara, CA, USA). The unit was connected to a Micro-Combustion Module^{TM} (MCM) device that eliminates interfering organic compounds potentially found in water samples through high-temperature oxidation (Saad *et al.*, 2013; Picarro, 2012). Analyses were conducted in high precision mode. Raw data were corrected for analytical effects (i.e., memory and drift) and normalized to the Vienna Standard Mean Ocean Water (VSMOW) scale using the protocols proposed by van Geldern & Barth (2012). Isotopic signatures of water were calibrated using internal laboratory standards calibrated against three International Atomic Energy Agency (IAEA) official standards, the VSMOW, the Greenland Ice Sheet Precipitation (GISP) and the Standard Light Antarctic Precipitation (SLAP). Precision of measurements was 0.1‰ for δ^{18}O and 0.3‰ for δ^{2}H based on repeated analyses of control samples.

Isotopic ratios are reported using the standard delta notation in per mil (‰) relative to VSMOW (Coplen, 1996):

$$\delta^{18}O \text{ or } \delta^{2}H = (R_{sample}/R_{VSMOW} - 1) \times 1000$$

where R is the heavy to light isotopic ratio ($^{18}O/^{16}O$ or $^{2}H/H$).

Figure 6. Study area and field work. a), b), c) and d) Overview of the landscape. e) Overland water flow after a rainfall event (U. Ilstedt). f) Sampling location with a soil pit under a Shea tree (background) and in the centre of the open area (foreground) (U. Ilstedt). g) Passive fibreglass wick lysimeter (U. Ilstedt). h) Soil pit under a Shea tree with two lysimeters installed at a depth of 150 cm in two opposite sidewalls (U. Ilstedt). i) HRM30 heat ratio sensor containing three probes. j) Drip-type Amsterdam rainfall simulator. k) Rainfall simulator plate seen from below. l) Dye

infiltration experiment under a tree associated with a termite mound. m) and n) Stained soil profiles.

3.5 Data analysis

3.5.1 Modelling groundwater recharge (paper I)

Groundwater recharge was modelled in Simile v5.9 (Simulistics Ltd.), a system dynamics and object-based modelling and simulation software, as a function of tree density and tree spatial distribution using a water budget approach. First, accumulated soil water drainage at a depth of 150 cm (expressed as % annual rainfall) was modelled over a spatial grid of 1 ha using the relationship found between accumulated water drainage and distance to the nearest tree stem. Second, estimated annual tree transpiration was subtracted from the accumulated deep drainage to obtain annual groundwater recharge. In order to explore the influence of tree size, three scenarios involving small, average and large trees were considered. To address the issue of how much water trees take up from below and above the 150 cm level, five scenarios were considered, with trees extracting 100%, 75%, 50%, 25% and 0% of transpired water from below 150 cm depth. Each model was run 100 times for 30 different tree densities ranging from 1 tree/ha to 70 trees/ha, and tree positions were randomized for each simulation. In addition, in order to evaluate the influence of tree spatial distribution on groundwater recharge, seven simulations (involving 1, 4, 9, 16, 25, 36 and 49 trees/ha) were run for regularly spaced, square distributions of trees.

3.5.2 Estimation of steady state infiltrability and degree of preferential flow (paper II)

Steady state infiltrability was estimated for each sampling position by fitting Philip's equation (Philip, 1957) to the set of soil infiltrability rates obtained during each rainfall simulation. When no runoff was generated during the simulation period, steady state infiltrability was assumed to be equal to the rainfall intensity (45 mm/h).

The pictures from the stained soil profiles were classified into dye-stained and nonstained classes using a supervised classification (Lillesand *et al.*, 2008) in ERDAS Imagine v9.3 image processing software (Erdas Inc., Atlanta, GA, USA). Preferential flow was quantified from the classified images by calculating five parameters as indices of preferential flow: dye coverage (Flury *et al.*, 1994), uniform infiltration depth (van Schaik, 2009), preferential flow fraction (van Schaik, 2009), length index and peak index. The two latter indices have been suggested by Bargués Tobella *et al.* (2014) as alternative ways to quantify the degree of preferential flow.

For each sampling position, a mean value of each of the calculated parameters of preferential flow was computed from the six vertical soil profiles. Wilcoxon signed-rank test was used to assess differences in steady state infiltrability and degree of preferential flow among sampling positions (open areas, single Shea trees, Shea trees associated with a termite mound), while Spearman's correlation test was used to evaluate whether, in open areas, steady state infiltrability and degree of preferential flow decreased with increasing distance to the nearest tree stem. The statistical analysis was performed with the package *stats* in R v3.0.1 (R Core Team, 2015) and the significance level was set to 0.05.

3.5.3 Determination of the relative contribution of different water sources to Shea tree water uptake (paper III)

The IsoSource mixing model (Phillips & Gregg, 2003), which is a multiple-source mixing model, was used to determine the relative contribution of different water sources to Shea tree water uptake. Different water sources were defined for both the dry and the wet season based on distinct $\delta^{18}O$ signatures of soil water found throughout the profile, while groundwater was treated as a separate source.

3.5.4 Evaluation of the effect of tree cover and rainfall intensity on soil water drainage (paper IV)

Amounts and isotopic signatures of rainfall and soil water drainage (at the 50 and 150 cm depths) collected in small and large open areas were used to evaluate the effect of tree cover on soil water dynamics in relation to rainfall intensity. Daily rainfall events were classified into three intensity classes: <10 mm/day, 10-20 mm/day, >20 mm/day. For each date on which a rainfall event was recorded, the mean soil water drainage at the 50 cm and 150 cm depths, as well as the mean value of the difference between rainfall amount and drainage at the 50 cm depth, was calculated for both large and small open areas.

In order to analyse the effect of rainfall intensity and opening size on the degree of evaporation of soil water drainage, the line conditioned excess (lc-excess) (Landwehr & Coplen, 2004) of a subset of soil water drainage samples was calculated using the local meteoric water line (LMWL) from Barogo (*ca.* 85 km northeast from Saponé) provided by Mathieu (Mathieu, 1993). The LMWL represents the relationship between $\delta^{18}O$ and $\delta^{2}H$ of the precipitation collected in a specific region, while the lc-excess expresses mathematically the offset between the LMWL and the analysed water samples: values close to 0 indicate little difference between the samples and the local precipitation, whereas negative values suggest that the water has undergone significant nonequilibrium evaporation, the more negative values indicating a higher degree of evaporation (Landwehr & Coplen, 2004).

Mann-Whitney test was used to assess differences in soil water drainage and lc-excess values between both large and small open areas and rainfall intensity classes. Statistical analyses were performed in Minitab 17 statistical software (Minitab Inc., State College, PA, USA) and the significance level was set to 0.05.

4 Results and Discussion

The four papers included in this thesis were intended to investigate the relationship between tree cover and soil and groundwater recharge in conditions typical of the seasonally dry tropics, and to reveal the specific processes controlling this relationship. Below, I present and discuss collectively the main findings from each paper. Further results and more detailed discussions are provided in the appended papers I-IV.

4.1 Relationship between tree cover and soil and groundwater recharge

4.1.1 Tree cover and soil water drainage

Data from papers I and IV revealed that deep (150 cm) soil water drainage was affected by tree cover, and more specifically by distance to the nearest tree stem. The proportion of annual rainfall percolating down to 150 cm soil depth was greatest around the edge of the tree canopy, and decreased both towards the tree stem and with increasing distance from the canopy edge in the open areas (paper I, Fig. 7). Therefore, little water was available for groundwater recharge both immediately around tree stems and in the open areas far away from any trees. In agreement with this, results from paper IV showed that small open areas received more water at 150 cm compared to large open areas.

In the open areas, there was a positive relationship between the distance to the nearest tree stem and the date on which the lysimeters installed at a depth of 150 cm recorded the first water following the beginning of the rainy season (paper I). The date on which the first drainage was recorded was, in turn, positively related to the annual accumulated soil water drainage at 150 cm. Thus, small open areas close to trees received more water at 150 cm depth and they received it earlier in the wet season compared to large open areas further away from trees.

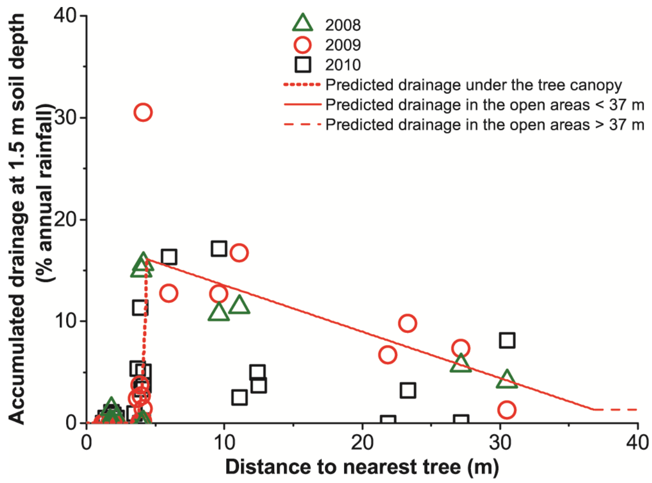

Figure 7. Relationship between the accumulated soil water drainage at 150 cm depth and the distance to the nearest tree stem. The lines show the relationships fitted to the 2009 data. Accumulated soil water drainage reached its maximum at 4.4 m from the nearest tree stem, which coincides with the approximate location of the canopy edge of a Shea tree of average size. Under the tree canopy, accumulated drainage increased exponentially towards the canopy edge ($y = 4.3\ 10 - 8\ e^{4.5\ x}$; Lack of Fit test indicated a suitable model; p=0.983), while in the open areas it decreased linearly with increasing distance from the nearest tree stem ($y = 18.1 - 0.46\ x$; $R^2_{adj}=0.69$, $p=0.013$).

4.1.2 Modelled groundwater recharge as a function of tree cover

In paper I, groundwater recharge was modelled as a function of tree cover using the relationship between deep soil water drainage and distance to the nearest tree stem described above (Fig. 7), along with data on Shea tree transpiration. Results from this modelling exercise show that groundwater recharge is maximized at an intermediate tree cover irrespective of the considered scenarios regarding the origin of transpired water (Fig. 8), tree size or tree spatial distribution, thereby confirming the overall hypothesis of this thesis.

When all water uptake scenarios are considered, the optimal tree canopy cover ranges between 4% and 23% (Fig. 8). However, findings from paper III can help constrain the most likely scenarios of water uptake by Shea trees, which in turn can be used to narrow the range of optimal tree covers for this site. Results from paper III indicate that Shea trees in the study area accessed different water sources depending on seasonal changes in soil water availability. During the wet season, Shea trees preferentially used water from the upper soil layers (10-50 cm depth), whereas during the dry season, when water availability in these surface layers was low, Shea trees shifted their use to deeper, more reliable water sources, including groundwater. Thus, the most extreme water uptake scenarios assuming that 100 and 0% of the water volume transpired annually by Shea trees is taken up below 150 cm depth can be discarded. By doing so, the resulting optimal tree canopy cover ranges between 5 and 10% (Fig. 8).

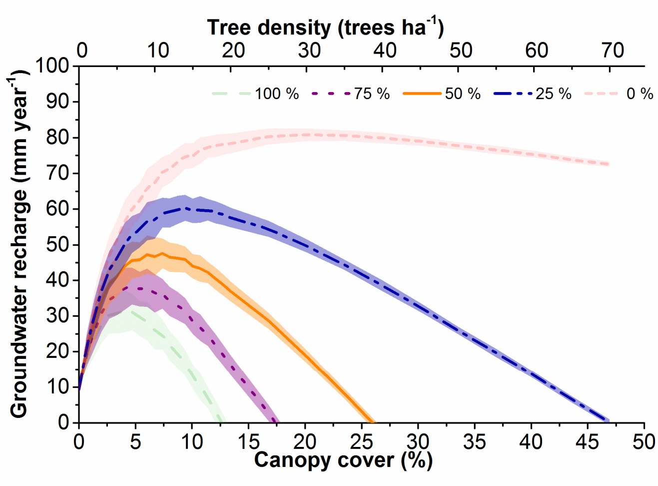

Figure 8. Spatial simulations of groundwater recharge in relation to tree density and canopy cover. For each of the 30 simulated tree densities, the means and standard deviations resulting from 100 simulations with random locations of trees across a 1 ha area are shown. The different colours indicate the proportion (0%, 25%, 50%, 75%, 100%) of tree water uptake occurring below 150 cm depth (note that the most unlikely scenarios of water uptake have been masked). Average tree size (67 m^2 canopy area) is assumed for all the simulations.

Findings from paper I not only support the hypothesis that in conditions typical of the seasonally dry tropics groundwater recharge can be maximized at an intermediate canopy cover; they also suggest that, at our study site, groundwater recharge is higher than in a treeless situation up to densities of *ca.* 20 to 60 trees/ha (Fig. 8).

4.2 Processes

Here, I would like to discuss the specific processes that explain the observed relationship between amount and timing of deep soil water drainage and distance to the nearest tree stem (papers I and IV).

4.2.1 Overview and main trends

The low amounts of accumulated deep drainage observed immediately next to tree stems (paper I, Fig. 7) are probably the result of tree transpiration and interception losses. But, what are the processes controlling deep water drainage further away from the stem? Results from paper II showed that both steady state infiltrability and degree of preferential flow were higher under Shea trees compared to the surrounding open areas. Greater steady state infiltrability and degree of preferential flow under trees, coupled with reduced soil evaporation, a possible decrease in canopy interception with increasing distance from the tree stem and the occurrence of canopy drip at the outer edge of the tree canopy are the processes that can explain why deep soil water drainage was highest in the area around the canopy edge. Results from paper II also indicate that, in the open areas, the degree of preferential flow decreased with increasing distance to the nearest tree stem, that is, the degree of preferential flow was higher in small open areas near trees than in large open areas further away from trees. However, findings from paper II did not reveal any relationship between steady state infiltrability and distance to the nearest tree stem in the open areas. These findings, however, are in disagreement with the results from another study conducted in the same study area which show that, in the open areas, steady state infiltrability did actually decrease with increasing distance to the nearest tree stem (Joelsson, 2012). Divergences between the results of these two studies are probably related to the fact that the latter measured steady state infiltrability at various positions along a transect from the tree stem to the centre of the open area, and thus was able better to capture the variation in steady state infiltrability within the entire open area. There are, therefore, two possible explanations behind the negative relationship between deep water drainage and distance to the nearest tree stem observed in the open areas (paper I). The first is that this is solely related to a decrease in the degree of preferential flow with increasing distance to the nearest tree stem, and the second is that it is a combination of both reduced preferential flow and soil infiltrability far away from trees.

4.2.2 The effect of individual trees: differences between areas under trees and adjacent open areas

A clear positive effect of Shea trees on soil hydraulic properties was observed in the study area. Under single Shea trees, both the degree of preferential flow and the soil steady state infiltrability were higher than in the adjacent open areas, whereas under trees with an associated termite mound preferential flow was further enhanced and steady state infiltrability was reduced (paper II). These findings are in agreement with other studies showing higher soil infiltrability rates under the canopy of scattered trees compared to open areas both in savannahs (Belsky *et al.*, 1993; Belsky *et al.*, 1989) and agroforestry systems (Joelsson, 2012; Hansson, 2006; Eldridge & Freudenberger, 2005) in drylands. Enhanced preferential flow, on the other hand, has been previously observed under shrubs and bush vegetation in drylands (Devitt & Smith, 2002;

Bromley *et al.*, 1997), but to my knowledge there are no previous studies on the effect of individual trees on the degree of preferential flow.

Soil hydraulic properties are improved under trees and other woody vegetation through the combined effect of litter inputs, root and faunal activity, and microlcimate, which in turn promote enhanced soil structure, aggregate stability and macroporosity (Joelsson, 2012; Dunn, 2000; Belsky *et al.*, 1993; Mordelet *et al.*, 1993; Belsky *et al.*, 1989). Macropores such as root and faunal channels serve as pathways for the preferential flow of water through the vadose zone (Beven & Germann, 2013; Devitt & Smith, 2002; Bromley *et al.*, 1997). In the study area, termites are probably the most abundant type of soil macrofauna. Termite activity further enhances macroporosity under trees through the construction of galleries and tunnels (Jouquet *et al.*, 2015; Lobry de Bruyn & Conacher, 1990), which explains why the degree of preferential flow was higher under Shea trees associated with a termite mound than under single Shea trees (paper II). However, despite termite activity promoting macroporosity, steady state infiltrability was lower under trees associated with a termite mound compared to single trees. Such reduction in soil infiltrability could be attributed to the presence of surface crusts around termite mounds resulting from termite activity, as observed by Janeau & Valentin (1987). It must be noted, though, that steady state infiltrability can vary markedly among different locations around termite nests depending on the presence/absence and characteristics of crusts and galleries at the soil surface (Jouquet *et al.*, 2015; Eldridge & Freudenberger, 2005). It is not surprising, therefore, that various studies have reported increases in soil infiltrability associated with termite activity (Leonard *et al.*, 2004; Mando *et al.*, 1996; Elkins *et al.*, 1986). Hence, despite the fact that soil infiltration may be very limited in locations closer to the termite mounds, as observed in paper II, it may be enhanced further away from them.

The actual impact of single trees on deep drainage and groundwater recharge will result from a balance between processes favouring water flow through the vadose zone and those involving water uptake or reduced water inputs. Among the first, there is the combined increase in soil infiltrability and preferential flow under trees (paper II), which implies not only that more water is able to enter the soil under trees, but that a fraction of this water will move rapidly throughout the profile along preferred pathways, thereby bypassing much of the soil matrix and readily reaching greater depths (Beven & Germann, 2013; Hendrickx & Flury, 2001). In addition, if soil moisture is enhanced under trees as a result of reduced soil evaporation (Abdallah & Chaieb, 2012; Sanou *et al.*, 2010), water flux through the vadose zone will increase. Among the negative impacts of trees, on the other hand, are increased rainfall interception and transpiration.

Findings from paper II also suggest that, in the study area, trees function as water harvesters. Median steady state infiltrability under single Shea trees was *ca.* 40 mm/h, whereas in open areas it was significantly lower (8 mm/h). Moreover, under trees, most of the measured steady state infiltrability values were above 30 mm/h, which corresponds to the median rainfall intensity at Ouagadougou (Hoogmoed & Stroosnijder, 1996), whereas in the open areas most of these values were below. This indicates that surface runoff (infiltration-excess overland flow) is easily generated in the open areas but not under trees, which in turn suggests that, at our study site, open areas act as sources of surface runoff, while trees may capture part of this water. Surface water redistribution from bare to vegetated patches is a common phenomenon in many dryland ecosystems (e.g. Ludwig *et al.*, 2005; Reid *et al.*, 1999; Bromley *et al.*, 1997), and can greatly modify the local water balance, as sink areas may end up receiving more water than the actual rainfall (Bromley *et al.*, 1997; Gaze *et al.*, 1997). Thus, the negative impacts of trees on soil and groundwater recharge through rainfall interception may not be so relevant in areas with high occurrence of surface runoff, at least as long as soil infiltrability under trees is high and surface runoff can flow from source open areas to areas under trees.

4.2.3 The effect of trees beyond their canopy edge: differences between open areas of contrasting size

Results from papers I, II and IV indicate that the positive effect of Shea trees on soil hydraulic properties and deep water drainage extended well beyond the canopy edge into the open areas, probably due to the influence of tree roots. Indeed, some studies suggest that for trees and shrubs the radius of the rhizosphere can be up to ten times larger than that of the canopy (Lejeune *et al.*, 2004).

In the open areas, deep drainage was enhanced close to trees compared to areas further away from any trees (papers I, IV). Annual accumulated soil water drainage at 150 cm decreased with increasing distance to the nearest tree stem (paper I). In addition, results from paper IV showed that median daily water drainage at 150 cm depth was *ca.* 12 and 9 times higher in small compared to large open areas under rainfall intensities of 10-20 and >20 mm/day respectively. However, findings from paper IV also indicate that, despite significant differences in drainage amounts at 150 cm depth, soil water drainage at 50 cm depth was not significantly higher in small compared to large open areas. This suggests, therefore, that the major process responsible for enhancing deep water drainage in the open areas was not soil infiltrability but rather preferential flow. This is in agreement with results from paper II showing that, in the open areas, the degree of preferential flow decreased with increasing distance to the nearest tree stem, whereas soil infiltrability did not change. Thus, in the large open areas far away from trees soil water flow occurred mainly as matrix flow, that is, water moved slowly downwards in the soil profile through the entire soil volume. In contrast, in small open areas close to trees, root channels enabled the preferential flow of water towards deeper soil layers. These contrasting flow mechanisms can lead to differences in the time needed for infiltrating water to reach deep layers, but also in the amount of water that reaches the deep layers, because water moving via matrix flow is more exposed to evaporation. This would explain why small open areas received more water at 150 cm depth and why they received it earlier in the wet season compared to large open areas (paper I). Moreover, lc-excess results suggest that soil water drainage at 150 cm in the large open areas had undergone more evaporation than in the small open areas (paper IV), which provides further support that the degree of preferential flow was higher in the small compared to the large open areas.

These findings are extremely relevant as they highlight the importance of trees in such systems to enhance deep soil water drainage, and eventually groundwater recharge, through the creation of macropores that facilitate the movement of water throughout the vadose zone. In drylands, preferential flow through macropores has been shown to contribute notably to groundwater recharge, to increase recharge rates and to reduce the time needed for water to reach deep soil layers (Mathieu & Bariac, 1996; Johnston, 1987b; Johnston, 1987a; Allison & Hughes, 1983).

4.2.4 The effect of rainfall intensity

Overall, higher daily rainfall intensities resulted in higher daily water drainage at 50 cm depth (paper IV). The increase in the amount of soil water drainage at 50 cm was particularly marked when rainfall intensity increased from <10 to 10-20 mm/day, which is in agreement with previous studies indicating that, in (semi)arid environments, small rainfall events result in no or little percolation (Small, 2005; Mathieu & Bariac, 1996; Barnes *et al.*, 1994; Gee & Hillel, 1988). However, when rainfall intensity increased from 10-20 mm/day to >20 mm/day only small open areas received significantly more water at 50 cm depth, suggesting that in large open areas very intense rainfall events do not necessarily promote the recharge of soil water, which can be linked to the occurrence of infiltration-excess overland flow.

Interestingly, greater rainfall intensities only resulted in enhanced deep water drainage (150 cm) in small open areas, whereas in large open areas deep drainage amounts remained low regardless of rainfall intensity (paper IV). Again, these differences can be attributed to the differences in degree of preferential flow, as discussed in the previous section. These results suggest, therefore, that in conditions typical of the semiarid tropics, tree-associated macropores may be key in enabling the recharge of deep soil water with increased rainfall intensities.

Moreover, results from paper IV suggest that higher rainfall intensities not only enhanced soil water drainage at 50 cm, but also overland flow. In semiarid West Africa, infiltration-excess overland flow is a widespread phenomenon, in particular following woodland or forest conversion into pasture or cropland (Favreau *et al.*, 2009; Lal, 1996). Overland flow can have severely detrimental impacts on agricultural productivity and local water supplies, as it promotes soil erosion and floods (Mahe *et al.*, 2010; Giertz *et al.*, 2005). As discussed earlier (4.2.2), scattered trees in drylands can act as water harvesters, capturing part of the overland flow generated in the open areas and thereby attenuating erosion.

4.3 Factors influencing the optimum tree cover for groundwater recharge

Findings described in this thesis demonstrate that groundwater recharge can be maximized at an intermediate tree cover. But, is this always the case? The specific tree cover value that maximizes groundwater recharge will depend on multiple factors, including local conditions related to climate, geology, soils and land use history, tree species and tree age. Given the various benefits conferred by trees and the importance of water supplies, it is essential to evaluate how these factors may influence the relationship between tree cover and groundwater recharge.

4.3.1 Optimum tree cover for groundwater recharge: no trees *vs.* intermediate tree cover

According to the *optimum tree cover theory* presented in this thesis, there is an optimum value of tree cover that maximizes groundwater recharge. Below this optimum, more trees will lead to improved groundwater recharge, as the benefits provided by these trees exceed their extra transpiration and interception losses. In contrast, above the optimum, more trees will result in less groundwater recharge, as the additional interception and transpiration losses from these trees dominate any positive effects they might have. Thus, the net impact of changes in tree cover on groundwater recharge will be the result of a balance between the positive and negative effects of trees.

An intermediate tree cover probably maximizes groundwater recharge under conditions typical of the seasonally dry tropics. These conditions consist mainly of a combination of inherently high rainfall intensities, high evaporative demand, and fine textured soils which are very sensitive to physical degradation (Bonell, 1993; El-Swaify *et al.*, 1983; Hoogmoed, 1983; Lal, 1983). When forests or woodlands are converted to other land uses such as cropland or pasture, the soils are easily degraded because of poor aggregate stability, leading to crust formation, reduced soil infiltrability and higher occurrence of infiltration-excess overland flow, which in turn can limit the recharge of soil and groundwater. Moreover, the combination of fine textured soils and high evaporative demand can easily result in high soil evaporation in the absence of macropores that allow some of the infiltrating water to bypass the soil matrix and rapidly reach deeper soil layers. Thus, starting from a point at which there are only few trees, soils are degraded and overland flow is prevalent, adding more trees will lead to enhanced groundwater recharge as long as their benefits through increased soil infiltrability, preferential flow and reduced evaporation exceed their transpiration and interception losses. Conversely, completely removing an open tree cover will probably result in less groundwater recharge, though there are some exceptions. In endorheic basins, for example, increases in the occurrence of overland flow from land degradation do not necessarily put at risk the recharge of soil and groundwater as would normally be expected. This is mainly because overland flow is unable to discharge into streams that leave the basin, but instead it is retained in internal ponds, lakes or swamps where it will either evaporate or recharge the soil and groundwater. This helps explain why woodland conversion into cropland and subsequent land degradation in an endorheic basin in southern Niger resulted in increased groundwater recharge (Favreau *et al.*, 2009).

There are certain situations in which the benefits of trees may be too low or absent, and thus groundwater recharge will probably be maximized in the absence of trees, as implied by the *trade-off theory*. For example, in some locations the soils can be too porous or the rainfall intensities too low for trees to make any difference to the amount of water entering the soil or the rates of water flow within the vadose zone. In other cases, human pressure may be so high (associated with actions such as litter collection, grazing and harvesting of fuelwood) that trees are not able to improve soil hydraulic properties (Ghimire *et al.*, 2013).

4.3.2 Factors under management control

There are a number of factors under management control that can influence the value of the optimum tree cover and the amount of groundwater recharge.

Different tree species have different characteristics that influence not only the amount of rainfall they intercept, how much water they use or where they obtain this water from, but also their net effect on soil hydraulic properties. Thus, tree species selection offers opportunities to maximize groundwater recharge and dry season flow. Tree characteristics such as canopy architecture, leaf area, leaf angle distribution and size of leaves and bark roughness, have a strong influence on interception, though rainfall intensity and duration also play a major role (Xiao *et al.*, 2000; Llorens *et al.*, 1997; Herwitz, 1985). Different tree species also differ in their water use. A study comparing water use and transpiration rates among ten tropical co-occurring broadleaved tree species showed considerable variation across species, with twofold differences between contrasting species of similar size (Dierick & Hölscher, 2009). In the agroforestry parklands of Saponé, Shea trees are rarely leafless and maintain high transpiration rates even during the dry season (Bazié, 2013), which is probably due to their capacity to access deep water sources during periods of water limitation in the upper soil layers (paper III). Tree species with different water-use strategies, such as drought-deciduous tree species, which use more shallow water sources and overcome seasonal water limitation by shedding their leaves (Schwendenmann *et al.*, 2015; Hasselquist *et al.*, 2010; Meinzer *et al.*, 1999), could lead to both higher groundwater recharge and optimum tree cover values. Different tree species might also exert contrasting influences on soil hydraulic properties considering differences in litter quality, root architecture, under-canopy microclimate or associated soil fauna. Indeed, there is some evidence suggesting that the effect of tree establishment and forestation on soil infiltrability differs among species (Malmer *et al.*, 2010), though more research on this topic is needed. In summary, favouring tree species that have strong positive impacts on soil hydraulic properties and low interception and water use may be a good strategy to improve groundwater recharge further.

Besides tree species, tree size also exerts a strong control over tree water use as indicated by the positive relationship between tree diameter at breast height (DBH) and water use observed for Shea trees (paper I) and other tree species (paper I, Dierick & Hölscher, 2009; Vertessy *et al.*, 1997; Vertessy *et al.*, 1995). However, there are indications that the relationship between DBH and whole-tree water use is less steep in older compared to younger forest stands, probably due to differences in leaf and sapwood area related to stand age (Wullschleger *et al.*, 1998; Vertessy *et al.*, 1997). Simulations based on the relationship between Shea tree DBH and water use reported herein showed that the groundwater recharge at optimum tree cover increased with decreasing size of individual trees (paper I). However, these relationships need to be studied in more detail in future experiments as it is possible that sap flow has been overestimated in this study, in particular for large trees (see paper I).

Tree spatial distribution can also influence groundwater recharge. Modelling results, for instance, suggest that a regular tree distribution can result in more groundwater recharge compared to a random distribution (paper I).

Moreover, management practices such as tree pruning or livestock control could further enhance groundwater recharge. In agroforestry parklands, crown pruning is a common practice and it has been shown to notably reduce tree transpiration rates (Bayala, 2002; Bayala *et al.*, 2002). Besides tree pruning, the management of livestock grazing also offers opportunities to improve groundwater recharge. High stocking rates typically have an adverse effect on soil infiltrability as a result of soil compaction caused by animal trampling and reductions in vegetation cover and organic matter in the topsoil, though maintaining light grazing intensities can be beneficial due to surface crust fragmentation and manure inputs (Savadogo *et al.*, 2007; Hiernaux *et al.*, 1999; Saleem, 1998).

Improved groundwater recharge can also be achieved through soil and water conservation (SWC) practices such as terracing, tillage on the contour or surface runoff harvesting ponds. In Burkina Faso, for example, Reij *et al.* (2005) reported local increases in groundwater tables in villages where SWC techniques (including traditional plating pits or zaï and contour stone bunds) had been implemented. This suggests that combining SWC practices with trees and some of the aforementioned management strategies could further enhance groundwater recharge.

4.4 Implications of the *optimum tree cover theory* for groundwater recharge

Trees provide multiple benefits, including carbon sequestration, income, nutritional diversity, livestock fodder, energy and biodiversity (Sinare & Gordon, 2015; Asbjornsen *et al.*, 2014; Shvidenko *et al.*, 2005). However, the establishment of trees in water-limited environments is often discouraged due to the prevailing view in forest hydrology that more trees lead, without exception, to reduced water availability. In contrast to this *trade-off theory,* findings reported in this thesis show that intermediate tree cover can enhance groundwater recharge and thereby increase dry season flows. That more trees can actually lead to improved water availability has profound implications for livelihoods and the environment. Tree-based landscape restoration and forestation of degraded lands can, if undertaken and managed properly, increase water availability at the same time as improving the livelihoods of local people and providing global benefits.

The fact that groundwater recharge can be maximized under an intermediate tree cover not only implies that more trees can lead to improved water availability, but also that decreasing tree cover can have the opposite effect. In the Sudano-Sahelian zone of West Africa, trees constitute major elements of the landscape and are usually integrated into the agricultural land. These so-called agroforestry parklands are the dominant farming system in the region and support millions of people (Boffa, 1999). In these systems, reductions in tree cover could have disastrous impacts on ecosystem services, agricultural production and livelihoods. Findings reported herein indicate that decreasing tree cover can result in diminished soil and groundwater recharge and a greater occurrence of overland flow, which suggests that there might be a higher risk of erosion, floods, agricultural droughts and water scarcity during the dry season. Thus, diminishing tree cover could potentially induce an ecosystem regime shift from a stable state in which some of the rainfall is able to recharge soil and groundwater, to an alternative stable state in which overland flow is predominant and occurs at the expense of soil and groundwater recharge. A possible future scenario for the agroforestry parklands is that tree cover is eliminated or seriously reduced to allow for agricultural mechanization. This could negatively affect the local population not only because of diminished groundwater recharge, but also due to reduced benefits from trees in general.

As mentioned earlier (1.3.2, 4.3.1), land degradation in endorheic basins may lead to enhanced groundwater recharge. But, at the expense of what? Favreau *et al.* (2009) reported increases in the groundwater level following woodland clearing for cropland expansion in southern Niger, but highlighted as well that this occurred at the expense of land degradation, with gullies developing and continuously increasing in number and length. The authors claim that if groundwater resources are used for irrigation this could improve crop yields, but seem to ignore the effects of land degradation and erosion on soil fertility. Thus, although groundwater recharge can increase as a response to woodland clearing, the concurrent land degradation and adverse effects on soil fertility should also be considered as they may outweigh any possible benefits from enhanced groundwater recharge.

Global warming is expected to intensify the global hydrological cycle. One important aspect of such hydrological intensification is the potential increase in the occurrence of extreme rainfall events. In the tropics, climate change projections predict an increase in heavy rainfall and, in some areas, simultaneous decreases in total precipitation; thus, there may be more heavy and episodic rainfall events interspersed with longer dry periods (Seneviratne *et al.*, 2012; Solomon *et al.*, 2007b). This is the case for West Africa, where an increase in the occurrence of extreme rainfall events and a decrease in mean precipitation and frequency of wet days is expected to occur during the 21st century (Sylla *et al.*, 2015). Results from paper IV suggest that, under a scenario with more intense rainfall events, maintaining a moderate tree cover may be essential both to enable a concurrent increase in groundwater recharge and to attenuate the occurrence of overland flow in many areas over the seasonally dry tropics. If tree cover is absent, there may be a risk that more intense rainfall events do not actually translate into enhanced groundwater recharge but only into increased overland flow as a result of limited soil infiltrability and preferential flow. Moreover, the effects in the long term may be even more pronounced, as more intense rainfall and higher occurrence of overland flow will probably reduce soil infiltrability further.

5 Conclusions

The overall conclusion of this thesis is that in conditions typical of the seasonally dry tropics groundwater recharge can be maximized at an intermediate tree cover. This is mainly because the net balance between the trees' positive and negative influences on groundwater recharge changes under different levels of tree cover.

The specific conclusions of each paper are:

I- Groundwater recharge can be maximized at an intermediate tree cover, thus confirming the *optimum tree cover theory*. Further increases in groundwater recharge can be achieved through various additional management options.

II- Tree cover has a positive effect on two major soil hydraulic properties influencing groundwater recharge, namely soil infiltrability and preferential flow. Termite mounds associated with trees may further increase the degree of preferential flow.

III- Partitioning of water resources by Shea trees in the study area is affected by seasonality and tree size. During the wet season, Shea trees preferentially accessed water from the upper soil layers, whereas during the dry season, when soil water availability in these layers was low, they shifted to deeper water sources, including groundwater. The switch to deeper water sources was particularly pronounced for smaller trees.

IV- Preferential flow through macropores is essential to enable deep percolation. Moderate tree cover promotes preferential flow and therefore has a positive effect in allowing increases in rainfall intensity to translate into enhanced deep soil and groundwater recharge. In contrast, in areas far away from the influence of trees, increasing rainfall intensity does not lead to significant increases in deep percolation.

In contrast to the prevailing view (*i.e.,* the *trade-off theory*), findings reported in this thesis demonstrate that the appropriate management of tree cover can enhance groundwater recharge in the seasonally dry tropics, offering opportunities for improving the livelihoods of millions of people in this region.

6 Future research directions

Understanding the links between tree cover, land use, soil hydraulic properties and hydrological flows is extremely important to generate better predictions of the net impact of changes in tree cover on groundwater recharge and dry season flows. This information, in turn, is essential to be able to formulate solid strategies and policies aimed at improving water availability.

The research described in this thesis contributes to our understanding of the relationship between tree cover and groundwater recharge in the seasonally dry tropics, but more work is needed in this field.

One research priority is to validate the extent of the *optimum tree cover theory*. Results from this thesis suggest that groundwater recharge will be maximized under an intermediate tree cover over widespread areas in the seasonally dry tropics, but more studies are needed to confirm this and to characterize the specific conditions under which this will be the case. In this regard, it would be very valuable to conduct paired-catchment experiments and supplement these with process measurements. Ideally, such experiments should be long-term and consider soil degradation, various tree species (including native ones) and intermediate degrees of tree cover.

Of particular interest, especially in the context of forestation and tree-based restoration of degraded lands in the tropics, is to clarify how improvements in groundwater recharge and dry season flow can be achieved through species selection. In this sense, much more needs to be known about how different tree species occurring in the tropics (both native and exotic) differ in terms of interception, water use and their effect on soil hydraulic properties.

Remote sensing techniques allow mapping individual tree crowns and species in open woodlands (Karlson *et al.*, 2015; Karlson *et al.*, 2014) and thus offer promising opportunities to upscale plot measurements to the landscape scale. However, to make this possible more plot-based measurements are needed in these systems. In this respect, research on tree water use should aim to establish species-specific allometric relationships that allow estimation of stand transpiration. More studies on the effect of trees on soil physical properties are also needed. Ideally, such studies should focus on investigating the spatial relationships between tree cover and soil properties related to soil and groundwater recharge (*e.g.* bulk density, organic carbon content, infiltrability and degree of preferential flow), taking into account the effect of tree species, tree size and other tree traits. Results reported herein indicate that, in the open areas, there was a negative relationship between degree of preferential flow and distance to the nearest tree stem. In the same study area, Joelsson (2012) and Dal (2016) also found significant relationships between distance to the nearest tree and bulk density, organic carbon content, infiltrability and macroporosity. Despite the fact that distance to the nearest tree stem seems to be a fairly good predictor of soil properties, further research is needed to clarify whether soil properties at a specific point in the landscape can be better predicted through the additive effect of multiple neighbouring trees, again considering tree species, tree size and other tree traits as well as their interactive effects. In addition, it would be relevant to study how different tree spatial configurations (random, regular, clumped) affect not only soil hydraulic properties, but tree water use and interception.

Again in the context of tree-based restoration activities, there is a need for a better understanding not only of the effect of different spatial configurations of trees and various tree densities on soil properties and groundwater recharge, but also of the temporal variability of these effects. Can soil hydraulic properties be restored through tree-based restoration? If so, under what conditions? What are the temporal changes in soil hydraulic properties following tree establishment? How do these changes vary spatially around individual trees or tree clumps and how are they affected by the initial degree of degradation, land use and management practices, tree cover and tree species? Studying the temporal changes in soil properties occurring in the opposite direction, that is, following removal of tree(s), is also highly relevant. Soil properties under and around trees will probably be maintained once trees have been removed, the question is how long does it take for them to decline to levels comparable to those found in areas far away from the influence of trees. Such knowledge is needed to evaluate if, for example, in agroforestry parklands groundwater recharge could be enhanced using a rotation system in which old trees are cut and new trees are established in large open areas.

Soil and water conservation practices deserve more attention too. In future experiments, it would be very interesting to evaluate the interactions between tree-based restoration and SWC techniques. For instance, are water harvesting techniques more effective in enhancing deep soil and groundwater recharge if combined with tree-based restoration?

Tree water source partitioning studies based on stable isotope techniques provide insights into the strategies trees use to overcome seasonal water limitation and provide valuable information to model the local water balance. In this thesis, I investigated the sources and patterns of water use by Shea trees. In the future, it would be interesting to do the same for other parkland tree species. In the context of agroforestry, water source partitioning studies are of great interest as they can provide very useful information on tree–crop interactions. Results from paper III showed that, during the wet season, Shea trees did not preferentially use water from the moister topsoil layer, but instead from slightly below this, which suggests that there might be a vertical niche partitioning in water source utilization between trees and crops. Finding out whether trees and crops in dryland agroforestry systems compete for the same water source or not is of great relevance but, to my knowledge, this has rarely been investigated using stable isotope techniques (with the exception of Smith *et al.*, 1997). It would be very interesting, therefore, to look further into this topic.

7 References

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