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CEPHaS - Strengthening Capacity in Environmental Physics, Hydrogeology and Statistics for Conservation Agriculture Research

Literature review – Assessing groundwater recharge estimates under conventional tillage and conservation agriculture

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Executive Summary

The purpose of this review is to identify studies from across the world that evaluated the impact of conservation agriculture (CA) on potential groundwater recharge in comparison to conventional tillage (CT), taking into consideration the techniques that have been used in measuring the soil or groundwater fluxes. In this review, we quantify case studies in which direct and indirect methods have been used to calculate a direct or proxy value of groundwater recharge under the different agricultural treatments of CA and CT.

This review revealed that CA systems have the potential to improve infiltration or deep drainage and therefore potential recharge to the groundwater as evidenced by 54% of the case studies, including all studies (n=5) in the SADC region, however significant proportion of studies, mainly from the Americas and Europe, also reported either reduced potential recharge or no significant difference under different treatments. A majority of these studies used infiltration rates as a proxy. This review demonstrates that consideration on the methods used in estimating infiltration rates is important when evaluating the impact of agricultural systems on groundwater recharge in different climate zones. Issues such as the infiltration measurement technique used, timing of the measurements within the season, rainfall intensity, and soil type, are some of the parameters that must be carefully stated in studies to allow the infiltration rates within and across treatments to be comparable.

The review revealed a gap in the literature for studies that used direct methods of recharge estimation to evaluate the impact of CA vs CT treatments. Unsaturated zone techniques provide only estimates of potential recharge based on drainage rates below the root zone and in some cases, drainage is diverted laterally and does not reach the water table. Use of direct methods that allow collection of data from the saturated zone such as groundwater level fluctuations in monitoring boreholes and environmental tracers such as Cl and stable isotopes of water, would be greatly beneficial to further our understanding of groundwater recharge processes beneath CA and CT systems. However, direct observations are more challenging to acquire and do have limitations.

Contents

List of Tables

List of Figures

1 Introduction

Conservation agriculture (CA) is defined as a farming system that is composed of three main crop management practices or principles: minimum soil disturbance or no tillage; crop or surface residue retention; and crop diversification or rotation (FAO, 2016; Indoria et al., 2017; Thierfelder et al., 2018). This system of agriculture was first formalised in the Great Plains of the USA in the 1930's, as a response to the "dust bowls" that arose from major erosion problems associated with a prolonged drought. Since then, CA has gained support such that almost every country has some activities that can be considered as CA (Derpsch et al., 2010; Kassam et al., 2014). In 1999 CA had been adopted on 45 million ha worldwide, 72 million ha in 2003, 111 million ha in 2009 and 125 million ha (9% arable land) in 2011 (Derpsch et al., 2015), translating to an annual increase of 6 million ha (Kassam et al., 2014).

The benefits of CA for farmers in arid to semi-arid climates have been reported as: improved performance of crops; efficient use of agricultural inputs; reduced risk of crop failure in dry periods; and an overall increase in the crop yield (Thierfelder et al., 2010). This is set against a backdrop of global losses in soil carbon stocks due to the effects of global warming (Crowther et al., 2016). For more humid areas (such as large parts of north-western Europe) farmers often face the challenge of excess water (Skaalsveen et al., 2019), and there, the interest in CA is its role in improving soil function to improve quality and flood mitigation (Skaalsveen et al., 2019). Some soil science and agricultural studies on CA treatments include increased infiltration and even increased recharge as benefits of the treatment over conventional methods (CT), however, there are few studies that have included a quantified assessment of CA treatments on groundwater.

Recent review studies have evaluated the effects of CA compared to CT on parts of the water balance, particularly infiltration rate, soil water storage, groundwater drainage below the root zone and potential groundwater recharge (Basche et al., 2019; Indoria et al., 2017; Skaalsveen et al., 2019; Ward et al., 2015). The review by Basche and Delonge (2019) gave a detailed meta-analysis of 89 studies that were used to evaluate how conventional practices affect infiltration rates relative to selected alternative practices (no-till, cover crops, crop rotation, introducing perennials, crop and livestock systems). Only studies that compared infiltration rates were considered in the review and no other parameter was considered. A conclusion of the Basche and Delonge (2019) review was that the overall effect of no-tillage (NT) treatments on infiltration rates was non-significant, only leading to increased infiltration in wetter climates (600 to 1000 mm annual precipitation) when NT was combined with residue retention.

In a review by Indoria et al. (2017) it was reported that many studies concluded that water retention and infiltration capacity increased in NT systems due to higher amounts of organic matter accumulated compared to tilled plots across different regions of the world, though the review did not include a quantification of the case studies nor the nature of the treatments compared and the field parameters measured. Another review of north-western European studies concluded that soil structural properties were often found to be poorer under NT than CT soils, resulting in decreased water infiltration rates and lower hydraulic conductivity, and that carefully selected cover crops could mitigate this effect (Skaalsveen et al., 2019).

Scanlon et al. (2002) noted that many of the studies that focus on measuring conditions within the unsaturated zone use terms such as “net infiltration”, “drainage”, or “percolation” to describe water movement below the root zone, and these are often inaccurately equated to groundwater recharge. The rate of movement of water in thick layers of the unsaturated zone can vary significantly below the root zone and at the water table, while in some cases drainage is diverted laterally and does not reach the water table (Scanlon et al., 2002). Many studies, therefore, by nature of the zone in which data is collected and techniques employed, can only be used to make statements on potential groundwater recharge estimates rather than actual recharge.

Significant increases in groundwater recharge have been observed following large-scale land use change from natural vegetation to tilled agriculture in the Sahel region of Africa (Leduc et al., 2001). A study by Scanlon et al. (2005) supported this observation after studies on the High Plains in Texas also showed that replacement of rangeland with agriculture changed flow directions from runoff (discharge) to downward (recharge).

The purpose of this current review is to identify studies from across the world that evaluated the impact of CA on potential groundwater recharge in comparison to CT, taking into consideration the techniques that have been used in measuring the soil or groundwater fluxes. In this review, we quantify case studies in which direct and indirect methods have been used to calculate a direct or proxy value of groundwater recharge under the different agricultural treatments of CA and CT. We use the term CA to refer to agricultural systems that employed either all three core CA practices or implemented only some of them, as well as all other synonyms of the practices such as reduced tillage and zero tillage (ZT) or no-tillage (NT).

2 Methodology

A systematic literature review was conducted to select and evaluate studies on the impact of CA or NT agricultural practices on potential groundwater recharge and is illustrated in Figure 1. Google Scholar was selected and a set of keywords established that included "Groundwater recharge" AND ["Conservation Agriculture" OR "no-till*" OR "zero-till*" OR "Crop rotation*" OR "Inter-cropping*" OR “water quality*”]. All articles were included, and these ranged from peer-reviewed, published articles to unpublished postgraduate research documents. Articles known to the authors (n=25) that did not come up in the Google Scholar search were also included from the onset of the review as articles identified. During the assessment of the eligible studies, references in articles that appeared to fit the criteria were also searched for and assessed and those found eligible were also included (n=4). Articles included in the final database met the following criteria: (i) a direct comparison of the same crop type grown on CA and CT; (ii) included studies that collected quantitative data through either in-field or laboratory techniques for measuring soil moisture, infiltration, percolation and recharge (direct and indirect groundwater recharge quantification); (iii) excluded studies of general land-use changes on groundwater recharge; and (iv) focussed on groundwater quantity studies rather than those dealing with groundwater quality aspects.

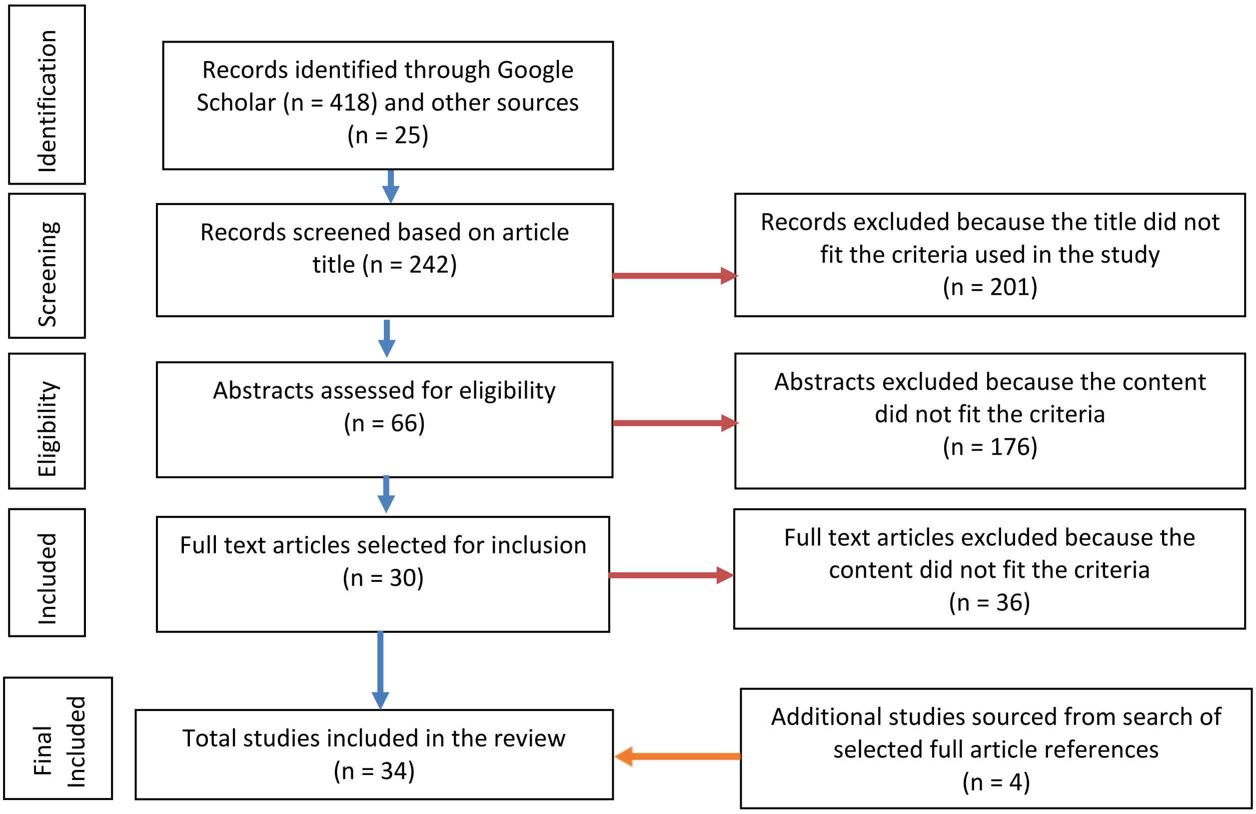


Figure 1 Flow diagram documenting the records of evidence found in the stages of the review

2.1 Methods of groundwater recharge assessment (direct and indirect)

Groundwater recharge estimation is a critical component of water resources management especially in semi-arid regions where water is scarce and projected climate trends may threaten this resource (Wang et al., 2010). Recharge estimation techniques based on surface-water and unsaturated zone data provide estimates of potential recharge, whereas those based on groundwater data in the saturated zone have the potential to estimate actual recharge (Scanlon et al., 2002). The selection of appropriate techniques to evaluate groundwater recharge evaluation is influenced by factors such as the purpose of the study, climate, geomorphology and geology (Scanlon et al., 2002). The reliability of the techniques varies and often researchers will employ more than one technique in a study.

Wang et al (2010) categorised groundwater recharge assessment methods into 2 groups, direct and indirect. Direct methods involve groundwater level monitoring while indirect methods involve the monitoring of changes in the components of the water balance equation and inferring or calculating the component that is estimated to move into groundwater storage. Quantifying groundwater recharge can be further categorised by the three possible zones of data collection namely surface water, unsaturated zone, and saturated zone; Figure 2 illustrates these methods. Surface and unsaturated zones are synonymous with the indirect methods described by (Wang et al., 2010). The specific techniques employed in these methods are represented in Table 1.

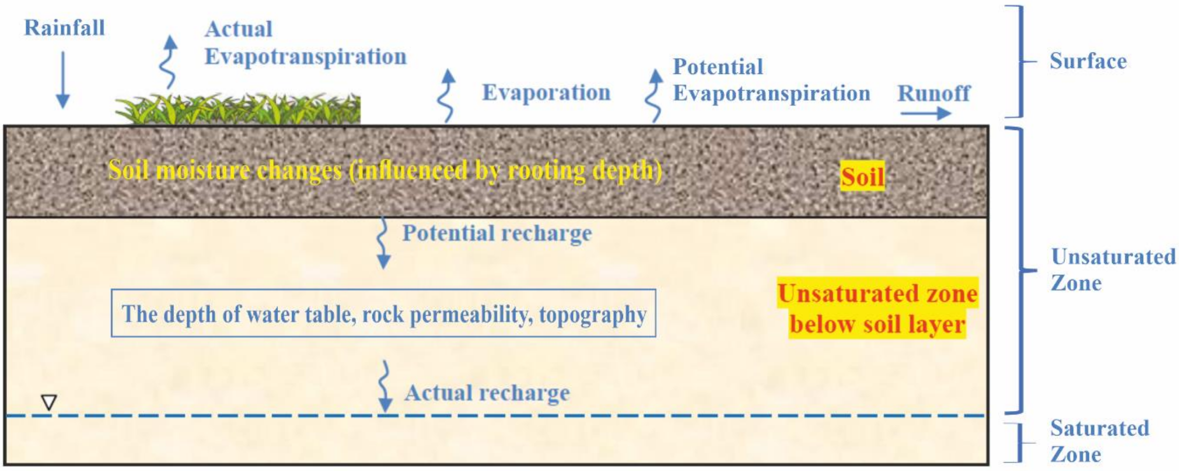


Figure 2 Factors affecting potential and actual groundwater recharge adapted from Wang et al. (2010)

Many agricultural or soil science studies that have been used to measure the impact of tillage methods focus on collecting data in the surface water and the unsaturated zones, making use of mostly physical methods to measure water fluxes, soil water, and infiltration (Elliott et al., 1999; Mupangwa et al., 2011; A. Ngwira et al., 2012). Scanlon et al. (2002) highlight that the different methods of recharge estimation have their pros and cons and the selection of the technique used should be based on the goal of the study and the required accuracy and reliability of recharge estimates. For example, water-budget approaches are generally less accurate in semi-arid and arid regions than in humid regions, because in dry areas recharge constitutes a smaller fraction of the water budget and the recharge term accumulates the errors in the other terms of the water-budget equation.

Direct or saturated zone techniques generally provide recharge estimates that are more reliable because they quantify actual recharge. These methods however can be more costly and more invasive requiring the use of drilling equipment for the establishment of monitoring boreholes. Also, the effects of other factors on water-table variability must be accounted for. In situations where long-established experiments exist implementing these direct measuring techniques without disturbing the existing surface conditions can be challenging. The use of environmental tracer techniques in the saturated zone can also be hampered by the application of agricultural inputs that can enter the groundwater system and affect recharge estimation methods such as the chloride mass balance. Another issue that poses a challenge for recharge estimation studies in agricultural systems is the size of the experimental plots. For soil water flux studies treatment plots of 10 m x 10 m or 0.25 – 0.5 ha are common; however, the response of the water table beneath is likely to integrate the effects of several plots, depending on the permeability and connectivity of the aquifer.

Table 1. Classification of techniques used in groundwater recharge (Scanlon et al., 2002; Wang et al., 2010)

Zone of data collection	Technique classified	Technique
Surface water	Physical	Seepage Baseflow discharge Chanel water
	Tracers	Heat tracers Isotopic chemical
	Numerical modelling: catchment modelling	
Unsaturated Zone	Physical	Lysimeters Soil moisture balance measurements
	Tracers	Applied (chemical or isotopic) Historical tracers (anthropogenic activities) Environmental tracers (e.g. Cl) Isotopic
	Numerical modelling: soil moisture balance	
Saturated Zone	Physical	Water-table fluctuation method
	Tracers	Groundwater dating Environmental tracers (Cl) Isotopic
	Numerical modelling: groundwater modelling	

2.2 Analysis

The information extracted from each of the articles as captured in Table 2 included the location details of the study site (country and coordinates); the details of the CA treatment applied; the zone of data collection and the technique used in the evaluation of soil and groundwater fluxes following the classification by Scanlon et al. (2002) and Wang et al. (2010). Where no direct value of groundwater recharge was available, data on water fluxes were used and values of increased infiltration, drainage/deep drainage, percolation, soil water content and runoff were used as proxy indicators of potential groundwater recharge. The overall impact on potential groundwater recharge was captured as either “higher in CA”, “higher in CT”, or “no difference” when there was no significant difference between the two treatment options.

3 Results and discussion

Results from the individual case studies at paired CA and CT sites are summarised in Table 2. Previous reviews and meta-analyses that were in the list of final articles, are not in this table but used in the discussion to compare with the results of this review.

Table 2 Summary of findings on impacts of tillage method on potential groundwater recharge

Country	Reference	CA method	Infiltration/ drainage / percolation measurement method	Direct	Indirect	Metric	Higher in CA	Higher in CT	No difference
Sudano-Sahelian zone	(Hoogmoed et al., 1991)	NT	Single ring infiltrometer soon after tilling		●	I		+	
			Single ring infiltrometer a day to 7 days after tilling						+
Malawi	(Ngwira et al., 2013)	CA with mulching & intercroppin g	Rainfall simulator and "time-to pond"		●	I	+		
Zimbabwe	(Mupangwa et al., 2008))	CA basins & ripper tillage	Water balance model		●	SWC	+		
Zimbabwe & Zambia	(Thierfelder and Wall, 2010)	CA rotation & ripper tillage	Rainfall simulator		●	I	+		
South Africa	(Kosgei et al., 2007)	NT	Time Domain Reflectometry (TDR) tube probe		●	SWC	+		
South Africa	(Mupangwa and Jewitt, 2011)	NT	Water balance model		●	DD	+		
Poland	(Lipiec et al., 2006)	NT	Double ring infiltrometer		●	I		+	
Australia	(Lawrence et al., 1994)	NT	Neutron Moisture Meter (NMM), runoff		●	SWC, I			
Australia	(O'Leary, 1996)	No-till with residues	Chloride mass balance in soils to 2m depth		●	R	+		
Australia	(Ward et al., 2011)	NT & cover crops	Neutron Moisture Meter (NMM)		●	D			+
China	(Xu et al., 2019)	Mulching in different textured farmland soils	Modified chloride mass balance	●	●	I	+		

Country	Reference	CA method	Infiltration/ drainage / percolation measurement method	Direct	Indirect	Metric	Higher in CA	Higher in CT	No difference
India	(Patil et al., 2016)	Residues, intercropping	Water balance model		●	Roff	+		
Syria	(Sommer et al., 2014)	NT	Falling-head, single-ring infiltrometer		●	I	+		
Canada	(Elliott and Efetha, 1999)	NT with rotation	Single ring infiltrometer		●	I	+		
USA	(Jones et al., 1994)	NT	Rotating-disk rainfall simulator		●	I		+	
USA	(Blanco-Canqui and Lal, 2007)	NT with residue mulch	Double ring infiltrometer		●	I		+	
USA	(Freebairn et al., 1989)	Short term (9 weeks) no-till and cover crops	Double ring infiltrometer		●	I		+	
USA	(Haruna, 2017)	NT & cover crop	Single ring infiltrometer		●	K	+		
USA	(Daniel, 1999)	NT	Groundwater level in monitoring wells	●		R		+	
USA	(Baumhardt et al., 2010)	CA with rotation	Cl concentration in soil		●	D	+		
Argentina	(Sasal et al., 2006)	NT	Disk permeameters		●	I			+
Brazil	(Schossler et al., 2018)	NT	Darcy's law for hydraulic conductivity		●	K		+	

N.B. NT = No-till a CA method at times used synonymously, CT = conventional tillage
D = Drainage, DD = Deep drainage, I = Infiltration, K = Hydraulic conductivity, R = Recharge, Roff = Runoff, SWC = Soil water content

Of the studies included in the review 41% (n = 9) were from America. Previous reports have indicated that North and South America accounted for approximately 85% of the world total land under CA in 2008/2009, while Africa was reported as having the lowest portion of area under CA or NT farming at 0.3% (Derpsch et al., 2010). Europe had the fewest manuscripts found that compared potential recharge under the different agricultural treatment options. Most of the studies (20 of n=22) employed techniques based on indirect measures of recharge to investigate the influence of CA practices on soil water content and the movement of water through the soil profile.

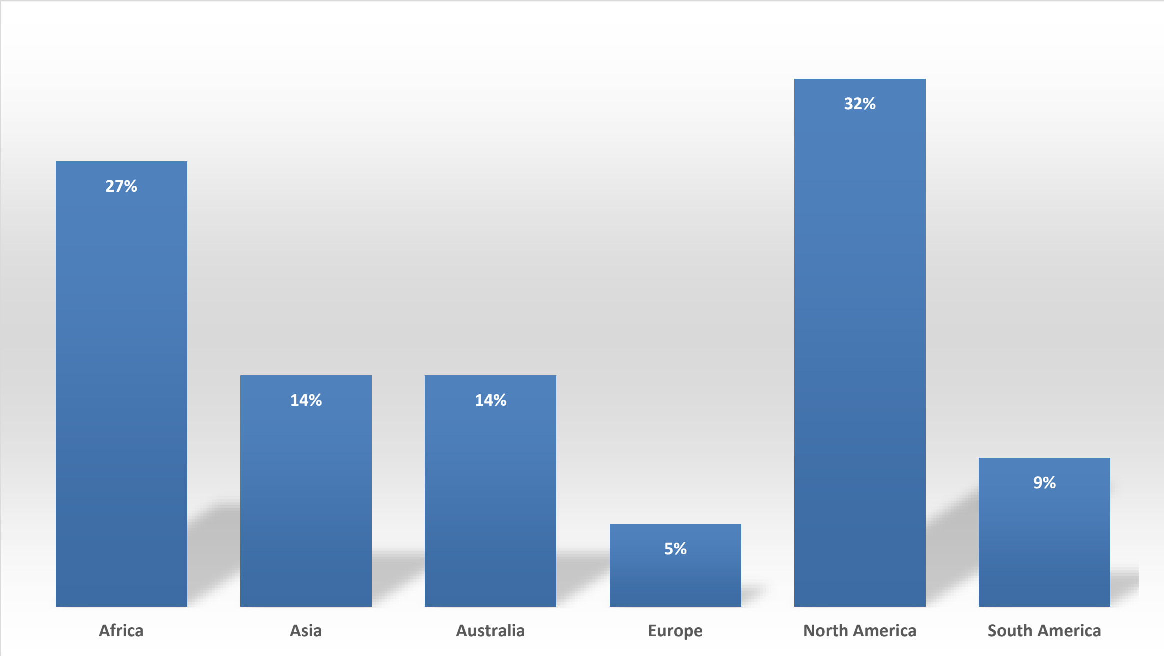
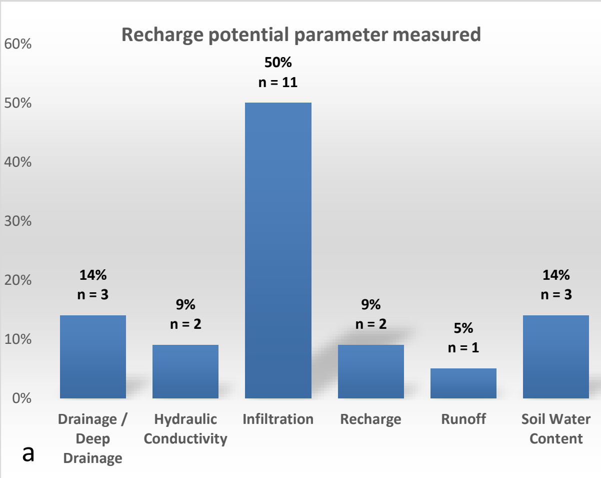


Figure 3 Manuscripts organised by the continent of the study site

3.1 Recharge estimation technique and potential groundwater recharge

In 54% of the studies, potential groundwater recharge was higher under CA treatments compared to 32% of the studies in which it was higher under CT, while 14% of the studies concluded that there was no difference between CA and CT practices (Figure 4). This result tallies with other reviews where CA was associated with faster rainfall infiltration in studies in Australia (Ward et al., 2015). In a USDA-Agricultural long-term study, runoff records showed that infiltration, and therefore potential groundwater recharge, could increase by more than 100 mm yr^{-1} in watersheds farmed with NT practices as compared to similar fields that were conventionally tilled (Edwards et al., 1990). There is a need to explain the variations in the current review of the 46% of the studies that were higher in CT or where there was no difference found. The influence of the diversity of CA treatments as well as methods employed in recharge estimation is a possible source of variations.

Direct measurement of recharge through groundwater level monitoring was used in a study by Daniel (1999) in which it was concluded that recharge rate was higher under CT (moldboard tilled) at 104 to 208 mm compared to NT that yielded 38 to 117 mm. In contrast, another study in northeast China calculated potential groundwater recharge rates using the modified chloride mass balance method in soils and groundwater (direct measurement) and rates of 41 – 44% higher in film mulched irrigation treatment plots compared to the plots without mulching (Xu et al., 2019). A study in Australia also corroborated this finding when potential recharge rate calculated over the 10 years of a tillage experiment using the chloride mass balance based on Cl measurements in soil water (indirect method), produced a value of between 18.5 - 18.6 mm year, with one additional recharge occurring on plots with NT and residue treatment compared to CT (O'Leary, 1996).



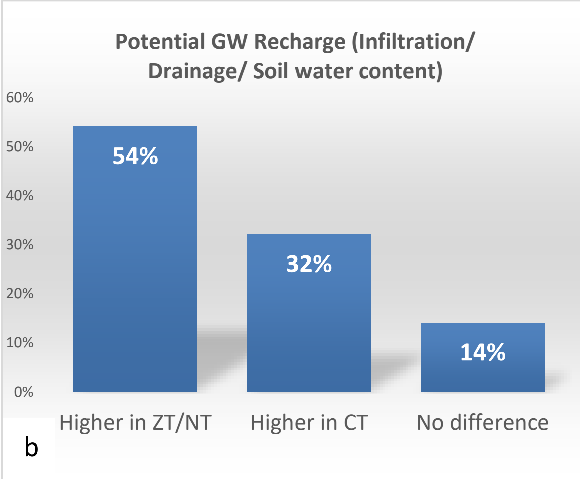


Figure 4 (a) Proportion of parameters measured in the studies reviewed and (b) the results presented regarding potential groundwater recharge

3.2 Infiltration rate and the impact on potential groundwater recharge

In one study by Hoogmoed et al. (1991), in which infiltration rates were measured in different treatments, records show that soon after tilling in the CT plots the onset of infiltration was delayed by 10 to 18 minutes in CT plots, however, once it started the rate of infiltration was higher in CT than CA and decreased more slowly in CT plots. With the CA treatment plots infiltration started sooner with the infiltration rate quickly decreasing within a short period. As the season progressed and with compaction of the soils, the onset of infiltration and infiltration rates were similar in CA and CT plots, however the cumulative infiltration under simulated rainfall was higher under CT compared to CA (Hoogmoed et al., 1991). This is an interesting observation as the time at which infiltration was measured in different treatment plots, among other factors such as soil type and rainfall intensity, influenced the infiltration rate, and the use of either total annual rainfall or event-based rainfall also impacted the result reported (Hoogmoed et al., 1991). In 7 of the studies reviewed, CA resulted in increased deep drainage and infiltration rates measured through varied methods (Baumhardt et al., 2010; Elliott et al., 1999; Mupangwa et al., 2011; A. R. Ngwira et al., 2013; Sommer et al., 2014; Thierfelder et al., 2010; Xu et al., 2019). Other reviews concur with this finding that CA generally increases water infiltration and improves available soil moisture, potentially reducing the negative effects of in-season dry spells (Indoria et al., 2017; Thierfelder et al., 2014). However, it has also been reported in some studies that infiltration is influenced by other factors such as soil type, which can lead to clogging (Thierfelder et al., 2014), and surface crusting associated with the NT system (Indoria et al., 2017; Jones et al., 1994).

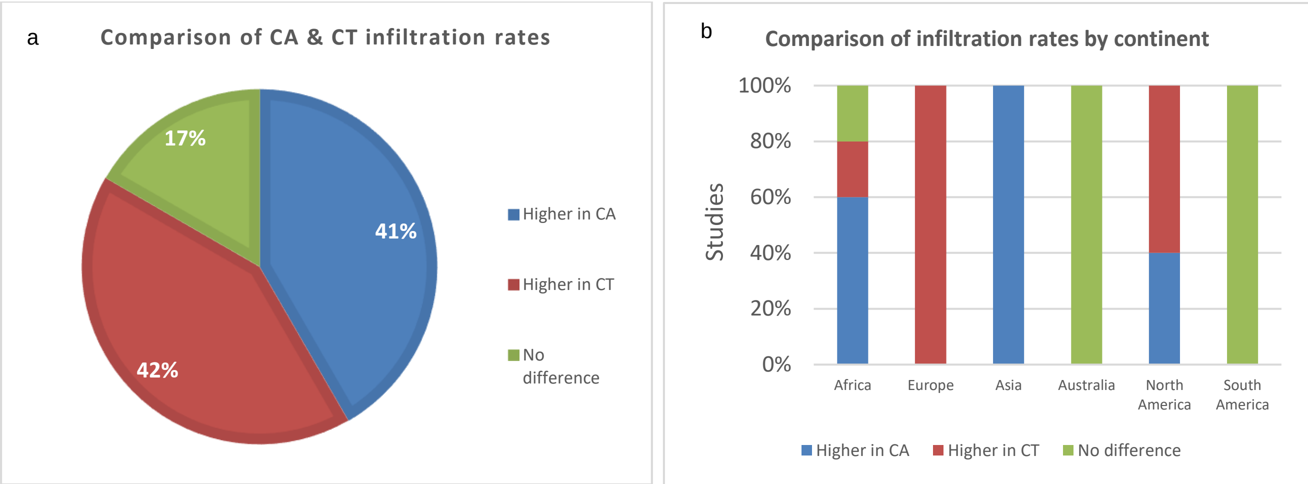


Figure 5 Comparisons of CA and CT infiltration rates in (a) all the studies and (b) by continent. (Africa (n=6), Europe (n = 1), Asia (n=3), Australia (n=3), North America (n = 7), South America (n=2))

3.3 Residue (mulching)/ cover crops and potential groundwater recharge

This review confirmed the varied combinations of treatment options that are available in the implementation of CA, and how these differences compounded the challenge of an analysis on the impact of the treatment options on groundwater recharge. In some studies, NT or reduced tillage treatments were assessed, while in others, NT was combined with residue applications of varied types such as stubble-mulch, film mulch, while in other treatments cover crops were also used.

Some studies reported on an increased hydraulic conductivity, and infiltration rate on treatments of NT with residue or cover crop inclusion (Haruna, 2017; A. R. Ngwira et al., 2013; Xu et al., 2019), while another study found that residue inclusion had a negative impact on infiltration resulting in cumulative infiltration being higher in CT plots than in short term NT plots (Freebairn et al., 1989). Another study concluded that straw mulching on NT plots significantly impacted hydraulic properties in the 0- to 3-cm soil depth ($P < 0.01$), resulting in a geometric mean of saturated hydraulic conductivity 123 times higher recorded in the NT plots, but water infiltration rate was unaffected (Blanco-Canqui et al., 2007).

In the review on numerous studies conducted in Australia in the 1980s and 90s using rainfall simulators and models, it was demonstrated that both stubble retention and reduced tillage led to faster rainfall infiltration and increased stormwater storage, however, it was not always the case, especially with NT and cover crops (Ward et al., 2015). Inconsistencies in the response of infiltration to NT with residue treatment could be explained by conclusions arrived at in a review of the studies, which were mainly from tropical zones, that a minimum of 2 t ha^{-1} of residues was needed to achieve the maximum effect on soil water infiltration, water runoff and soil loss control (Ranaivoson et al., 2017). In their review, Ranaivoson et al. (2017) concluded that a twofold increase in infiltration was recorded in treatments where 2 t ha^{-1} or more of residues were applied compared to bare soil and that a covered soil could increase soil water infiltration rate fourfold compared to bare soil. A meta-analysis of 34 studies (over 60% from USA, and others from Europe) found that cover crops reduced water drainage in more than 90% of the studies (Meyer et al., 2019). In another review they concluded that while there was a mean increase in infiltration rate owing to the use of cover crops, this was influenced by other factors such as the number of years of treatment (higher for over 4-year plots), and the soil type where the rate was higher in more coarse sandy soils than clay rich soils (Basche et al., 2019).

3.4 Crop rotations and potential groundwater recharge

In this review the combined treatments of NT with crop rotations were found to impact positively on measured drainage and infiltration rates (Baumhardt et al., 2010; Elliott et al., 1999; Ward et al., 2011). Calculated soil water drainage with NT averaged 11.4 mm annually or almost double the 6.3 mm yr^{-1} flux rate estimated for the region while Cl displacement exceeded the rooting depth only with NT, increasing the potential to recharge the groundwater. In an evaluation of results from 2005 to 2011 of maize in rotation and association with different crops in Malawi, Mozambique, Zambia and Zimbabwe, rotation with or without legumes improved water infiltration by between 70 and 238% (Thierfelder et al., 2013).

4 Conclusion

This review revealed that CA systems have the potential to improve infiltration or deep drainage and therefore potential recharge to the groundwater as evidenced by 54% of the case studies, including all studies (n=5) in the SADC region. However a significant proportion of studies, mainly from the Americas and Europe, also reported either reduced potential recharge or no significant difference under different treatments. A majority of these studies used infiltration rates as a proxy. This review demonstrates that consideration on the methods used in estimating infiltration rates is important when evaluating the impact of agricultural systems on groundwater recharge in different climate zones. Issues such as the infiltration measurement technique used, timing of the measurements within the season, rainfall intensity, and soil type, are some of the parameters that must be carefully stated in studies to allow the infiltration rates within and across treatments to be comparable.

The review revealed a gap in the literature for studies that used direct methods of recharge estimation to evaluate the impact of CA vs CT treatments. As explained by Scanlon et al. (2002), unsaturated zone techniques provide only estimates of potential recharge based on drainage rates below the root zone and in some cases, drainage is diverted laterally and does not reach the water table. Use of direct methods that allow collection of data from the saturated zone such as groundwater level fluctuations in monitoring boreholes and environmental tracers such as Cl, would be greatly beneficial to further our understanding of groundwater recharge processes beneath CA and CT systems. However, direct observations are more challenging to acquire and do have limitations.

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CEPHaS - Strengthening Capacity in Environmental Physics, Hydrogeology and Statistics for Conservation Agriculture Research

The CEPHaS project is a network of researchers from Zimbabwe, Zambia, Malawi and the UK. We bring together soil physicists, geophysicists, hydrogeologists, agronomy and farm system specialists and statisticians. We are developing the capacity of our network to deliver research on the impacts of CA on the water cycle via field experiments with cutting-edge monitoring, from the rooting zone to the water table, and associated laboratory capability. We are engaged with policymakers to deliver evidence concerning the impacts of CA on crop yields and groundwater recharge. We are also working positively to develop institutional environments that are conducive for world-class research through structured approaches to research capacity strengthening.

We believe that building such research capacity is essential for robust scientific evaluation of interventions to improve the resilience of rain-fed agriculture in the region, and to understand its impact on water security more generally.

To find out more, visit our webpages at https://www2.bgs.ac.uk/CEPHaS and follow us on twitter @CEPHaS_Soil

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