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Water regulation by grasslands: A global meta-analysis

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Abstract

Grasslands have been modified and replaced worldwide and have affected water regulation ecosystem services. In order to support public policies attending to the consequences of different grassland modifications and replacements, general patterns and models about their consequences on water regulation are needed. We quantitatively meta-analysed the results of 110 site-specific studies analysing infiltration (83) and evapotranspiration (28) responses to grasslands alterations by grazing, crops, and afforestation and how these responses vary with environmental factors. In grasslands, soil water infiltration is significantly reduced by grazing and cropping on average by 51% and 57%, respectively. Water infiltration is increased by 65% in response to afforestation. The reduction of infiltration with grazing decreases with soil sand content and increases with the mean annual precipitation (PPT) and the ratio PPT/mean annual potential evapotranspiration. The replacement of grasslands by forests increases evapotranspiration by 30%, and the variation of this response was linearly related to PPT and the PPT/mean annual potential evapotranspiration ratio. There was a negative trend in evapotranspiration responses although not significant, when grasslands were replaced by crops or modified by grazing. Our meta-analysis was able to reveal average patterns and the influence of local climate and soil properties on eco-hydrological responses to grasslands modifications and replacements, which have not been previously described. These results may support general predictive models on the influence of land use changes and ecosystem services provision. Significant gaps were found in the number of studies, especially of evapotranspiration, precluding the achievement of a general conclusion regarding evapotranspiration and infiltration responses.

KEYWORDS
eco-hydrology, ecosystem services, evapotranspiration, infiltration, land use/land change

1 | INTRODUCTION

Natural grasslands have been replaced, modified, and/or fragmented by agriculture, afforestation, invasion of non-native species, modification of fire regimes, desertification, urbanization, grazing, and trampling by domestic livestock (Gibson, 2009). These alterations have independent and interactive effects on ecosystem structures and processes that may influence the provision of relevant ecosystem services, especially those that do not have a clear market value such as regulation services (Baeza & Gallego, 2014; Booman et al., 2012; Nosetto, Paez, Ballesteros, & Jobbágy, 2015; Sala & Paruelo, 1997; Wilcox & Thurow, 2006).

There are consistent evidences about the impact of grasslands transformations and replacement on carbon and nitrogen soil content and soil erosion (Bartley et al., 2006; Fu et al., 2011; Miller, Belote, Bowker, & Garman, 2011; Wu & Tiessen, 2002) and water quality (Scanlon, Jolly, Sophocleous, & Zhang, 2007). In contrast, studies about the effect of grassland transformations and replacements on soil hydrological properties and their consequences on water regulation show contradictory results (Day & Detling, 1994; Fischer et al., 2013; Hoshino et al., 2009; Noellemeyer, Frank, Alvarez, Morazzo, & Quiroga, 2008; Yüksek, Tilki, & Yüksek, 2012) and therefore cannot be generalized. However, a systematic review of published results may help improve the current understanding of grasslands on water regulation. Our attempt to understand the hydrological responses to land use/land cover (LULC) changes over grasslands is based on two key biophysical processes related to the water cycle: soil water infiltration and evapotranspiration (ET).

Water infiltration brings support to relevant ecosystem services such as water provision and water purification (Viglizzo, Jobbágy, Ricard, & Paruelo, 2016), as well as with potential topsoil loss by erosion and run-off (Wischmeier & Mannering, 1969). Infiltration is mostly determined by soil texture and structure (Koorevaar, Menelik, & Dirksen, 1983). LULC changes can affect soil structure differently due to changes in root distribution, soil microbial activity, organic matter content, soil moisture, bulk density, porosity, and hydrophobicity (Dexter, 1991; Greenland, 1981; Greenwood & McKenzie, 2001). The magnitude of these modifications could be affected by different climate conditions. Asner, Elmore, Olander, Martin, and Harris (2004) and Oesterheld, Loreti, Semmartin, Paruelo, and Walker (1999) proposed that in mesic environment, soil properties have more resilience to grazing. Besides, soil compaction, a key process that affect infiltration, depends on the soil water content, soil texture and structure, and organic matter (Nawaz, Bourrie, & Trolard, 2013; Quiroga, Buschiazzo, & Peinemann, 1999). As it was found by Horn, Domżżał, Słowińska-Jurkiewicz, and Van Ouwerkerk (1995), when silt loam soils, with low colloid, have low water content, they are more susceptible to compaction than medium or fine textured loamy and clayey soils.

ET is closely linked to vegetation characteristics because it is affected by rainfall interception, net radiation, advection, turbulent transport, canopy resistance, leaf area, and available soil water (McNaughton & Jarvis, 1983; Zhang, Dawes, & Walker, 2001). Meteorological variables and soil properties interact with vegetation features in the control of ET. In arid and semiarid regions, ET is mainly controlled by available soil water and canopy resistance, whereas in humid regions, ET mainly depends on advection, net radiation, leaf area, and turbulent transport (Rodriguez-Iturbe, D'Odorico, Laio, Ridolfi, & Tamea, 2007; Zhang et al., 2001).

By applying a global meta-analysis of individual case studies from the peer-reviewed literature, two specific questions were addressed: (a) How are the ET and infiltration processes affected by different land cover changes (from grasslands to crops or to forests) and/or land uses (grazing) and (b) how LULC changes impact ET and infiltration in different climates and soils. We hypothesized that infiltration and ET are reduced by grazing or by the replacement of grasslands with crops and that they are enhanced when grasslands are replaced by forest. We also expected that the effects of LULC changes on ET and infiltration vary along environmental gradients. It is likely that the ET responses would be higher under the most favourable growing conditions (e.g., higher temperature, precipitation, or lower aridity conditions), although we expected a greater reduction in infiltration in more compactable soils (e.g., fine soils texture, high water content, and low organic matter).

2 | METHODS

2.1 | Literature search

To understand the effects of the LULC changes in grasslands on ET and infiltration, we systematically searched in Scopus and Scholar Google for peer-reviewed studies using the following combination of terms: (evapotranspiration OR transpiration OR infiltration OR "hydraulic conductivity" OR permeability) AND (replace* OR transform OR afforest OR deforest OR forest OR reforest OR wood OR "land use" OR degrade OR grazing OR crop OR cultivated OR pasture OR livestock OR cattle OR trampling) AND (grass OR graz* OR rangeland* OR pasture OR savannah* OR forage* OR herbage* OR meadow OR praire OR steppe). The search resulted in 2,455 articles including papers until 2016. We checked all references of papers revealed in the database search. We followed an exclusion process where we first examined twice the title and abstract of the total articles to exclude those that clearly do not focused on comparisons of infiltration or ET in grasslands and other types of vegetation. We downloaded all the articles that met the above criteria. Then we excluded those studies that did not perform pairwise contrast, between grasslands replaced by crop or forest and grasslands with grazing effects. Then we excluded the articles that had not reported statistic design, statistical measures (mean values, sample size, and variance estimation), evidence of reasonable comparing conditions of soil type, climatic conditions, and methodology. Those studies that met all the criteria above were included in the meta-analysis to evaluate the mean magnitude of replacement of grassland on infiltration or ET changes. Those studies that did not include data of sample size or variance estimates of infiltration or ET measurements were only included in a later analysis (explained in Section 2.3).

2.2 | Data extraction and database building

A database with 138 comparisons (Table S1) was constructed, based on 110 studies that met the criteria mentioned above. For each selected study, we extracted data of infiltration or ET as a response variable, as well as the country where the study took place, grassland status (degraded or not according to the authors criterion), and LULC changes (grazing effects or type of replacement vegetation—crops or forest). We included environmental data of the study site: mean annual precipitation (PPT) and mean annual potential evapotranspiration (PET); these data were extracted from Gleam database 3.0 (2001–2012; Martens et al., 2017; Miralles, De Jeu, Gash, Holmes, & Dolman, 2011), and an aridity index PPT/ETP was performed. We also included mean annual temperature. For infiltration studies, we also extracted data of soil texture (percentage of sand and clay), soil structure (bulk density), and the depth of infiltration measurement (we selected a threshold depth of 0–20 cm). In some studies, the variables were measured in grasslands that had been recovered by exclosure to livestock, so studies were classified according to their successional status as secondary (recovered) or primary. We also examined and registered the time since the replacement of the exclosure of the grassland occurred.

2.3 | Statistical analysis

The effect size is a statistical measure that portraits the degree to which a given event is present in a sample (Cohen, 1969). In a meta-analysis, the effect size is estimated from individual studies and pooled to calculate an overall effect size with associated statistical significance (Hedges, Gurevitch, & Curtis, 1999). The selected studies varied substantially in the kind of hydrological processes that they compared, and in the type of methodology used to measure them. Therefore, we chose the response ratios (RRs) as a measure of the effect size. The RRs were calculated as $[\ln(\bar{x}_{\mathrm{LULC}}/\bar{x}_{\mathrm{grassland}})]$, where $\bar{x}$ represents the average steady infiltration rate or saturate or near saturation hydraulic conductivity in infiltration studies and the average of the annual ET or mean ET during the growing period, for both the grasslands and the LULC of the studies. Positive or negative RRs indicate that infiltration or ET is greater or lower in the LULC than in the grassland, respectively. To quantify the effects of LULC changes on ET (RR_{ET}) and infiltration (RR_I) relative to crops and forests (LC), and grazing (LU), we calculated 10 types of RRs for each measure of infiltration and ET extracted from the studies (Table 1). RRs were also evaluated in terms of the control grassland status (if it was degraded or not). In addition, in infiltration studies where bulk density data were available, we calculated the RR_{BD} as $[\ln(\bar{x}_{LULC}/\bar{x}_{grassland})]$, where $\bar{x}$ represents the average bulk density.

The effect of the successional stage of grasslands on the RRs was tested by comparing primary versus secondary grasslands within each LULC and status of the grassland using *t* test. The relation between the effect of time since the recovery of the secondary grasslands and the RR_I was explored by fitting linear models using RR_I as a response variable and the years of exclosure as the explanatory variable.

A categorical (LULC) random-effect meta-analysis model was used to calculate the mean effect sizes assuming a random variation among observations, and 95% confidence intervals were calculated around the mean effect sizes using bootstrapping with 999 iterations (Rosenburg, Adams, & Gurevitch, 2000). Effect size estimates were considered significantly different from zero if their 95% confidence interval did not include zero. The required information for this analysis (mean, sample size, and variance estimates) was available for only 95 of the 138 comparisons (66 for infiltration and 29 for ET analysis). To check for publication bias, we calculated Rosenthal's fail-safe number (Rothstein, Sutton, & Borenstein, 2006), which indicates how many studies reporting zero effect size would need to be added to the meta-analysis to render the observed effect statistically insignificant. We obtained a fail-safe number of 164 for the ET and 326 for the infiltration analysis, suggesting no publication bias in our meta-analysis. We also checked for publication bias using funnel plots (Figure S1; Ellis, 2010). RRs calculations and statistical analyses were performed using MetaWin 2.0 (Rosenburg et al., 2000).

To explore if the RRs were affected by environmental variables, we fitted linear and nonlinear (polynomial and logarithmic) regression model equations for each type of LULC (crops, forest, or grazing). We used RRs as a response variable and the climate (mean annual precipitation, the ratio mean annual precipitation/potential ET, and temperature) and soil features (percentage of clay and sand) as explanatory variables. The influence of bulk density on changes in infiltration processes induced by grasslands replacement was examined using Spearman's rank correlation between infiltration RRs and bulk density RRs_{BD}.

3 | RESULTS

3.1 | Overview of the analysed studies

The 110 studies included in this analysis were conducted in 34 different countries. Forty-three studies were located in America, 27 in Asia, 20 in Europe, 10 in Africa, and 10 in Australia. ET measurements were reported in 28 studies, whereas infiltration measurements in 83 of them. According to the Koppen–Geiger climate classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), 14% of the infiltration studies corresponded to tropical wet climates, 56% to subtropical wet, 23% subtropical arid, 1% tropical arid, and 6% to cold climates (polar). Regarding the ET studies, 65% corresponded to subtropical wet, 23% subtropical arid, and 12% to cold climates (polar or snow; Figure 1). We did not find any ET studies from tropical, wet, or arid climates.

The successional stage of the control grasslands was primary stage (68 studies), secondary stage (39 studies), and both stages (three studies). The mean time of recovery of the secondary grasslands was 22 years (standard deviation: 21, minimum: 2, and maximum: 100). The studies included two different types of replacement vegetation: crops (46 studies, including wheat, soybean, potato, maize, millet, oats, barley, bean, cabbages, rape, and canola), forest (26 studies, including the genus *Pinus*, *Populous*, *Eucalyptus*, *Prosopis*, *Larix*, *Hevea*, *Tectona*, *Ceratonia*, and *Quercus*), and 48 studies corresponded to grazing effects. In average, the time since grasslands were replaced by crops or forests was 32 and 51 years, respectively. Although the average time since the grassland was exposed to grazing was 26 years, the different techniques used to measure infiltration were equally represented: single and double ring infiltrometer, tension infiltrometer, soil core, Guelph permeameter, and rainfall simulator. The techniques used to measure ET included eddy covariance, Bowen ratio, satellite image estimation (Landsat), lysimeters, soil–water balance derived from soil moisture measurements, and a chamber attached to a portable infrared analyser. The latter was used in only one study.

3.2 | Effect of LULC changes on soil infiltration

When we compared the RR_I calculated with control grasslands that had a secondary successional stage against those with primary stage,

TABLE 1 Response ratios calculated in the meta-analysis

Hydrological process	Land cover change		Land use change	
ET	GND to C	$RR_{ET} = ln(\bar{x}_C/\bar{x}_{GND})$	G to GGZ	$RR_{ET} = ln(\bar{x}_{GGZ}/\bar{x}_G)$
	GD to C	$RR_{ET} = ln(\bar{x}_C/\bar{x}_{GD})$		
	GND to F	$RR_{ET} = ln(\bar{x}_F/\bar{x}_{GND})$		
	GD to F	$RR_{ET} = ln(\bar{x}_F/\bar{x}_{GD})$		
Infiltration	GND to C	$RR_I = ln(\bar{x}_C/\bar{x}_{GND})$	G to GGZ	$RR_I = ln(\bar{x}_{GGZ}/\bar{x}_G)$
	GD to C	$RR_I = ln(\bar{x}_C/\bar{x}_{GD})$		
	GND to F	$RR_I = ln(\bar{x}_F/\bar{x}_{GND})$		
	GD to F	$RR_I = ln(\bar{x}_F/\bar{x}_{GD})$		

Note. Land cover change: C = crop; F = forest; GND: nondegraded grassland; GD: degraded grassland. Land use change: G = control grassland without grazing; GGZ = grassland with grazing.

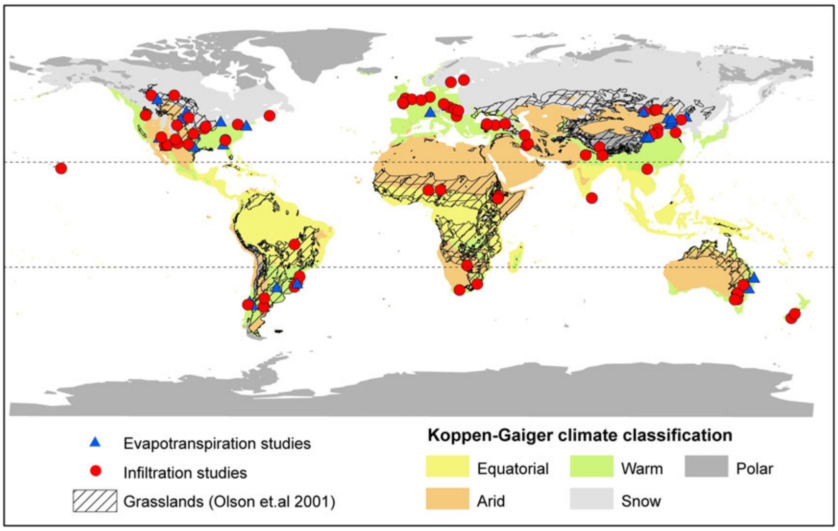

FIGURE 1 Distribution of the 110 selected studies over the worldwide map of Köppen–Gaiger climate classification

no significant difference was found within each LULC change and status of the grassland ($RR_{I[GNDtoC]}$: $t = -1.31$; p value = .21; $RR_{I[GDtoC]}$: $t = -1.77$; p value = .09; $RR_{I[GtoGz]}$: $t = 0.639$; p value = .527; $RR_{I[GDtoF]}$ $t = 0.949$; p value = .36; $RR_{I[GNDtoF]}$ $t = -0.465$; p value = .646). The relation between $RR_{I[GtoGz]}$, $RR_{I[GtoC]}$, and $RR_{I[GtoF]}$ and the years of grazing exclosure (2° grasslands) was not significant (p value: .79, p value: .794, and p value: .396, respectably). For this reason, these two variables (successional stage and years of exclosure) were not incorporated in the following analyses.

The replacement of nondegraded grasslands with crops ($RR_{GND\ to\ C}$; Table 1) decreased infiltration by 57% (Figure 2a). However, when degraded grasslands were included ($RR_{GNC\ to\ C} + RR_{GD\ to\ C}$; Table 1), the reduction of infiltration was not significant (Figure 2a). The grazing effects also caused a significant decrease in infiltration by 51%. On the other hand, forestations significantly increased infiltration by 65% (Figure 2a).

Even though most of studies measured saturated hydraulic conductivity or steady-state infiltration, five studies measured unsaturated hydraulic conductivity (four comparison of crops and one of forestation). We excluded these comparisons of the analysis, but the result did not change significantly. The replacement of nondegraded grasslands with crops ($RR_{I(GNDvsC)}$) decreased infiltration by 73% (95% CI [−1.03, −0.43]), but when degraded grasslands were included ($RR_{I(GDvsC)}$), the reduction of infiltration was not significant. Only one study measured unsaturated hydraulic conductivity on forestations, so when we excluded from the analysis, infiltration significantly increased by 59% (95% CI [0.098, 1.09]). No grazing studies measured unsaturated hydraulic conductivity.

The infiltration studies were performed along a wide range of annual PPT: 32% of the studies had an annual PPT < 500 mm, 49% had PPT between 500 and 1,000 mm/year, and only 19% had PPT >1,000 mm/year. Only $RR_{I(GvsGz)}$ was negatively related to PPT and to PPT/PET (Figures 3a,b and S2 and Table S2). The mean annual temperature ranged from 0 to 25 °C (6% of the comparisons had mean temperatures <3 °C, 31% had temperatures between 3 and 10 °C, and the remaining 63% had mean temperatures >10 °C). We did not find a significant relation between temperature and any RR_I (Figure S2 and Table S2). The soil texture in the different studies varied from clayey to sandy. Only $RR_{I(GvsGz)}$ had a significant logarithmic relation with percentage of sand (Figures 3c and S2). No significant interactions were found between these environmental variables (PPT, temperature,

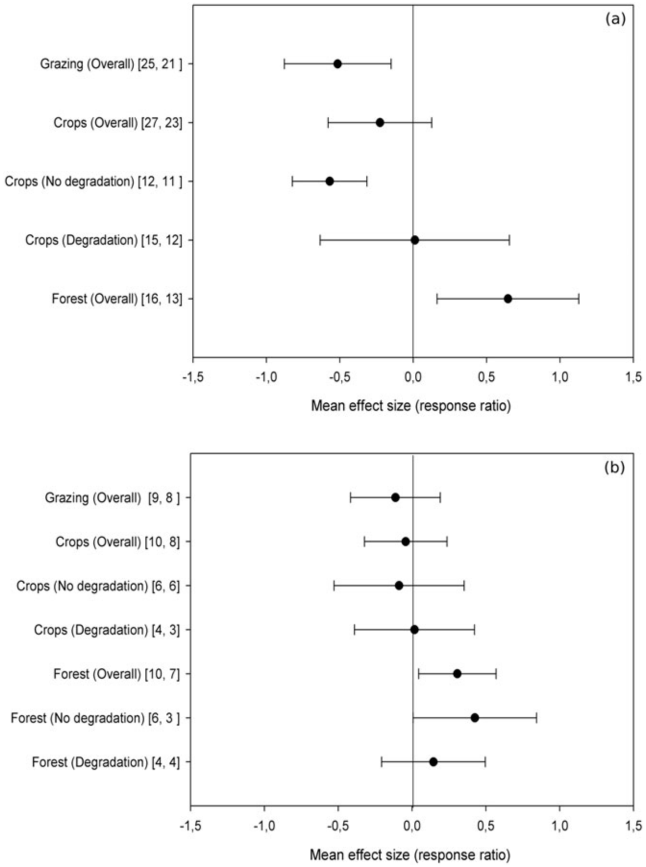

FIGURE 2 Mean effect size (response ratio) for infiltration (a) and evapotranspiration (b) in grasslands relative to land use/land cover (grazing, crops, and forest), across the primary studies. Bars around the means denote bias-corrected bootstrap 95% confidence intervals. Mean effect size is significantly different from zero if the 95% confidence interval does not include zero. The status of the grassland is described between parentheses (overall = no degradation + degradation grasslands). The first and second numbers in square brackets indicate how many comparisons and how many studies were included in each calculation, respectively

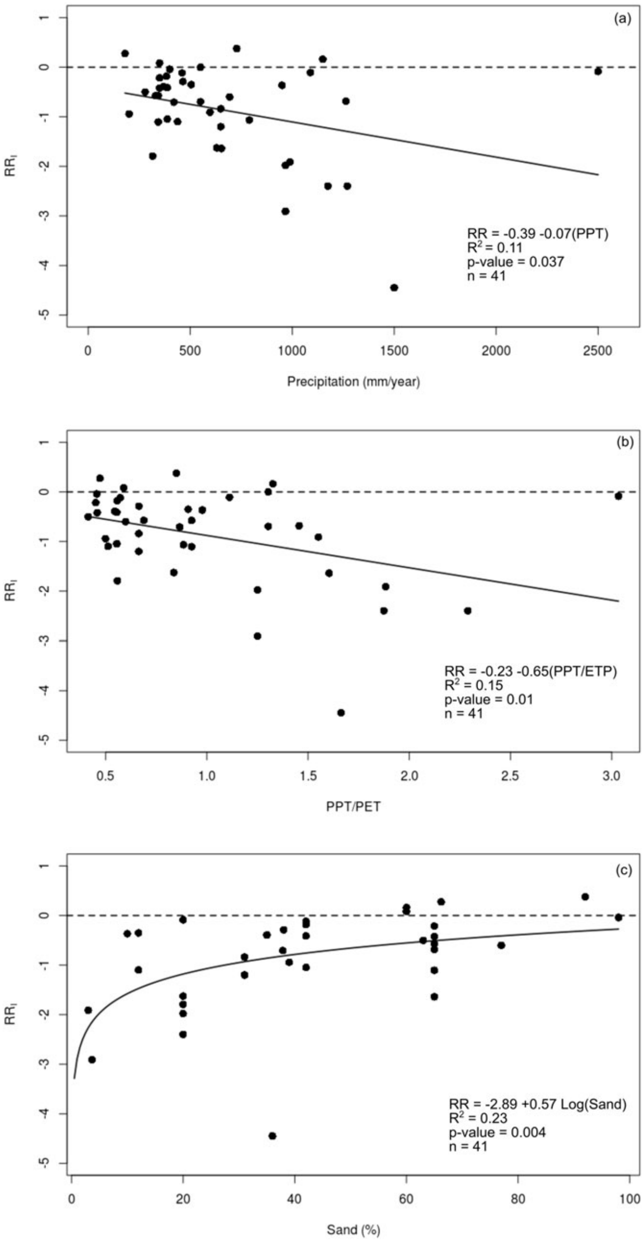

FIGURE 3 Regression model fit between $RR_{I(G\ to\ GGZ)}$ and (a) mean annual precipitation (PPT), (b) PPT/mean annual potential evapotranspiration (PET), and (c) percentage of sand

clay, or sand). Regarding bulk density, the RR_I and the RR_{BD} were significantly negatively correlated (Rs = −0.3, *p* value = .03, *n* = 52; Figure 4).

3.3 | Effect of LULC changes on ET

When we compared the RR_{ET} of the control grasslands that had a secondary successional stage against those with a primary stage, no significant difference was found within each LULC change ($RR_{I[GNDvsC]}$: *t* = −2.74; *p* value = .09; $RR_{I[GvsGz]}$: *t* = −1.28; *p* value = .22; $RR_{I[GDvsF]}$: *t* = −0.23; *p* value = .82). The $RR_{I[GNDvsF]}$ and $RR_{I[GDvsC]}$ were not analysed because no control grasslands had a secondary successional stage. The relationships between $RR_{I[GtoGz]}$, $RR_{I[GtoC]}$, and $RR_{I[GtoF]}$ and the years of grazing exclosure (2° grasslands) were nonsignificant (*p* value: .79, *p* value: .794, and *p* value: .396, respectably). For this reason, these two variables (successional stage and years of exclosure) were not incorporated in the following analyses.

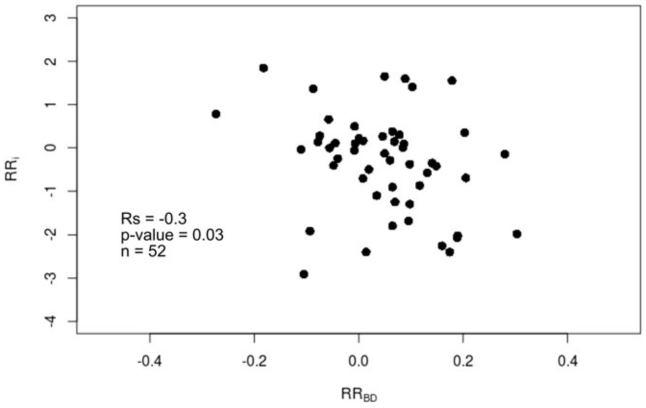

FIGURE 4 Spearman ranks (Rs) correlation between RR_I and RR_{BD}

The replacement of grasslands by forests increased ET by 30% (Figure 2b). No significant effect on ET was found when grasslands were replaced by crops (Figure 2b). However, when we compared degraded grassland versus crops and nondegraded grassland versus crops, the percentage of ET change rises 2% and decreases 8%, respectively. On the other hand, grazing caused a mean decrease of 11% on the ET, but the effect was not significant (Figure 2b). Five studies (six comparisons) measure ET only during the growing season (two of crop and four of grazing), and no significance changes were detected for all the above tests when repeated after excluding the studies performed during the growing season (two comparisons between grasslands and crops and four comparisons between grazed and ungrazed grasslands).

The ET studies were performed along a wide range of annual PPT (50% of the comparisons had PPT < 500 mm/year, 20% had PPT between 500 and 1,000 mm/year, and 30% had PPT > 1,000 mm/year). The $RR_{ET(GtoF)}$ were linearly and significantly related to PPT and PPT/PET (Figures 5a,b and S3). The mean annual temperature range was 0–25 °C (28% of the comparisons had temperatures <3 °C, 10% had between 3 and 10 °C, and 62% of the comparisons had temperatures >10 °C). There was no significant relation between temperature and RR_{ET} (Table S2 and Figure S3). However, we found a negative interaction between PPT and temperature in $RR_{ET(GtoF)}$ (Table S2), indicating that in warmer climates, the effect of PPT on ET afforestation is lower than in cold climates. We were not able to fit a regression model between ET and soil texture because of the low number of studies that gave this information.

4 | DISCUSSION

4.1 | Effect of LULC changes on hydrological processes

Infiltration is a soil property with a remarkable variability both in space and time. Thus, its estimation requires an adequate and intensive sampling design that precludes large-scale (large extent) observations. Therefore, meta-analysis procedures are a very useful approach to explore the large-scale variability that affects infiltration due to LULC changes.

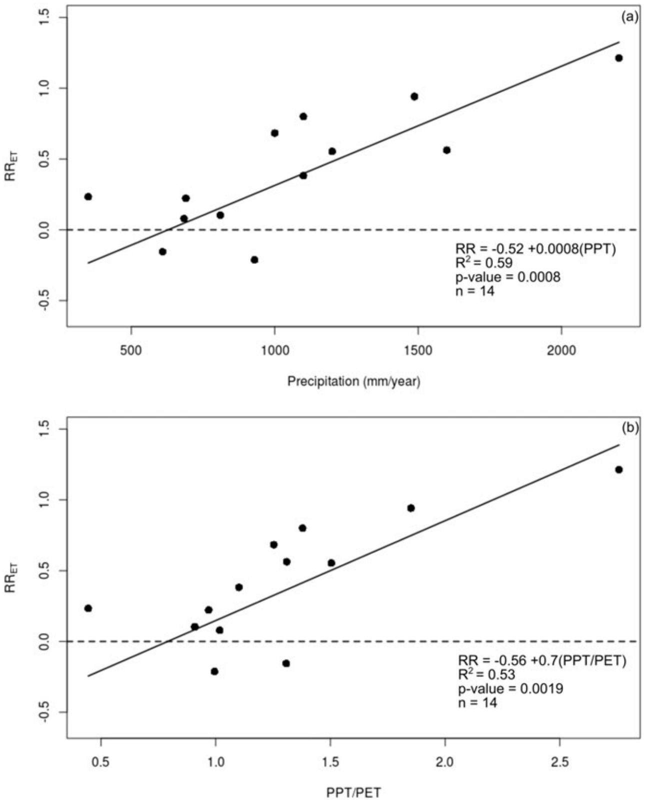

FIGURE 5 Regression model fit between $RR_{I(G\ to\ F)}$ and (a) mean annual precipitation (PPT) and (b) PPT/mean annual potential evapotranspiration (PET)

This meta-analysis confirms the hypothesis that grazing and cropping affect negatively the infiltration process, reducing it by 51% and 57%, respectively. On the other hand, afforestation produces a positive effect, increasing infiltration by 65% (Figure 2a). Regarding ET changes, there was a clear rise with afforestation (30%; Figure 2b), but no changes were detected when grasslands were grazed or replaced by crops (Figure 2b).

In general, the changes in infiltration were negatively correlated to changes in bulk density (Figure 4). This increase in bulk density is strongly associated with soil compaction due to cattle trampling or to the use of heavy agricultural machinery (Bodhinayake & Cheng Si, 2004; Chyba, Kroulík, Krištof, Misiewicz, & Chaney, 2014; Drewry & Paton, 2000; Li, Yan, Qingfeng, & Zhikaun, 2012; Zeng, Zhang, Wang, Chen, & Joswiak, 2013). Compaction causes a spatial rearrangement and alteration of the size and shape of aggregates. Consequently, the macroporosity is affected due to the modification of pore spaces and distribution (Defossez & Richard, 2002; Hillel, 1998; Spohn & Giani, 2010).

We did not find significant differences between the RR_I of primary and secondary grasslands. This finding agrees with previous reports on the recovery of soil physical properties in grasslands after the exclusion of grazing (Drewry, 2006) and crops (Wu & Tiessen, 2002).

Regarding the relation of RR_I with environmental variables, grazing reduces infiltration to a greater extent in environments with higher PPT/ETP ratio and PPT, and in soils with lower sand content, probably due to the influences of these factors on trampling effects on soil bulk density (Panayiotopoulos, Papadopoulou, & Hatjiioannidou, 1994). Soil compaction depends on the soil water content, soil texture and structure, organic matter, among others (Nawaz et al., 2013). At low water content, silt loam soils with low colloid content are more susceptible to compaction than medium or fine textured loamy and clayey soils, whereas sandy soils are slightly less susceptible to soil compaction (Horn et al., 1995). On the other hand, soil compaction vulnerability increases as soil organic matter decreases. Soil organic matter is positive correlated with clay content (Jobbágy & Jackson, 2000). Therefore, finely textured soils have greater soil aggregate stability and macropore structure (Basaran, Erpul, & Ozcan, 2008). The direction of the change in soil organic matter content is dependent of the interaction between texture, PPT, intensity of grazing, and grass type (McSherry & Ritchie, 2013). However, this was not possible to explore in the present analysis because of the low number of studies that provided information about the effect of grazing on the soil organic matter content.

The enhancing effect of grasslands afforestation on infiltration broadly agrees with the meta-analysis obtained by Ilstedt, Malmer, Verbeeten, and Murdiyarso (2007) for afforestation of croplands. However, the increments of infiltration that we found for grasslands were much lower than those observed for croplands, probably because infiltration in nondegraded grasslands is generally higher than in croplands (Figure 2a). Therefore, both meta-analyses offer a complementary view and reinforce the idea that afforestation could help enhance the infiltration of former cultivated lands and grasslands. This improvement in infiltration agrees with reductions in compaction and bulk density by afforestation as we could see in the negative correlation between RR and RR_{BD} (Figure 4). Therefore, reduction on bulk density by afforestation could be associated to greater organic matter, root density, less machinery, or animal trampling (Abbasi, Zafar, & Khan, 2007; Evrendilek, Celik, & Kilic, 2004; Price, Jackson, & Parker, 2010; Schwendenmann & Pendall, 2006).

The methodologies used to assess ET are more heterogeneous than those applied to the infiltration and mostly depended on the vegetation structure. In the cases of a homogenous vegetation cover, ET was typically modelled using weather data and algorithms that describe surface energy and aerodynamic characteristics of the vegetation. On the contrary, when the vegetation cover was heterogeneous (e.g., natural grasslands), the ET was usually evaluated through in situ estimations of water consumption, which included strong empirical and local characteristics (Allen, Pereira, Howell, & Jensen, 2011).

In accordance with many local studies, grazing tended to reduce ET (e.g., Bremer, Auen, Ham, & Owensby, 2001; Frank, 2003; Li et al., 2015 and Miao et al., 2009), with a mean value of 11%, but this reduction was not statistically significant. To better understand the grazing effect on ET, it is important to know the partition between transpiration and evaporation and how the net primary production is affected. Grazing reduces plant cover by removing litter and reducing the leaf area index, which in turn leads to an increase of the evaporation component. On the other hand, different grazing intensities affect the transpiration component (Peng et al., 2007; Reichert et al., 2017; Verón, Paruelo, & Oesterheld, 2011), so the trade-off between both processes makes it difficult to find a clear tendency.

In the cases where grasslands were replaced by crops, we did not find a significant change in the ET. Nevertheless, the tendency was opposite when the grassland control was degraded or not (Figure 2). In average, crops have a low mean annual leaf area index because of their relatively high proportion of bare soil (Sterling, Ducharne, & Polcher, 2012). This leads to higher evaporation losses from crops than from grasslands, but at the same time, the transpiration rates from crops are low because of a shorter growing period. Due to differences in the surveyed articles regarding the types of crops (C3-C4), crop rotation (single or double cropping system), grassland stage (primary or secondary), and the degree of degradation (degraded or not), combined with the low number of studies that separate ET components, we cannot state a clear conclusion of the effect on ET when grasslands are replaced by crops.

The effects of afforestation showed a clear increment on ET, in agreement with other reviews of pair-catchment studies (Hewlett & Hibbert, 1967; Hibbert, 1965). Only three comparisons had higher ET in grasslands respect to forests. The linear relationship between $RR_{ET(GvsF)}$ and PPT allowed us to conclude that afforestation in humid climates produces a higher increase of ET. One reason that could explain this relation is the fact that forests have a higher aerodynamic conductance, albedo, and higher root depth that allows them to extract deeper soil water (i.e., higher ET rates) than grasslands (Zhang et al., 2001). The ET of forests is restricted in dry places because of low water availability; whereas in humid areas, the ET of forests is greater than in grasslands because there is no water limitation (Calder, 1998; Kelliher, Leuning, & Schulze, 1993; Zhang et al., 2001). We found that this relation interact with temperature (Table S2), indicating that for places with the same PPT but higher temperature is expected to find lower rise on ET (for PPT range of 350–2,200 mm/year and temperature range of 6–25 °C).

Some studies provided data on annual ET values, whereas others only provided data during the growing season. However, when we excluded the studies that only measured ET during the growing season, we could not find differences in the tendency. This is important to mention because the ET might have been underestimated when it was only measured in the growing season in those cases where we compared annual versus perennial vegetation.

4.2 | Meta-analysis advantages and limitations and recommendations for future research

Meta-analyses have proven to be a powerful statistical tool in ecological reviews (Ilstedt et al., 2007; McSherry & Ritchie, 2013) because they allow the statistical assessment of a hypothesis by combining experimental data from several independent studies (Arnqvist & Wooster, 1995). In addition, it is possible to relate different variables that could explain general and underlying processes. This meta-analysis features a reasonable number of studies (N = 110) and independent contrasts (N = 138), compared with other meta-analyses with an ecological focus on grasslands (Loydi, Eckstein, Otte, & Donath, 2013; McSherry & Ritchie, 2013) or with an eco-hydrological focus (Ilstedt et al., 2007; Thompson, Harman, Heine, & Katul, 2010). To the authors' best knowledge, this is the first meta-analysis that includes ET estimations. Our review shows that there are significant gaps in the published literature because we found few independent studies about infiltration and specially, about ET. It is important to highlight the scarcity of studies from the tropics (only 15 cases of infiltration), despite that 10 years passed from of a former meta-analysis observing this fact (Ilstedt et al., 2007). This can be related to the main extent of grasslands in higher latitudes, rendering most of grassland studies within the great plains in North America, the Steppes of China and the Pampas of South America, and only 10 infiltration studies (and no ET studies) within de African grasslands.

Identifying and quantifying how the hydrological processes respond to LULC changes have several limitations due to (a) the scarcity and the short length of hydrological records (particularly in underdeveloped regions) along with few reported small-scale experimental studies, (b) the high natural variability of most hydrological systems; (c) the difficulties in "controlling" land use changes in real catchments, and (d) the challenges of extrapolating or generalizing results from such studies to other systems (DeFries & Eshleman, 2004).

Despite all the above-mentioned limitations, in this meta-analysis, we were able to reveal average patterns and the influence of meteorological variables and soil properties on eco-hydrological responses to grasslands modifications and replacements, which were not previously described. These results may support the development of general indicators and models about the influence of land use changes on the provision of hydrological ecosystem services, such as water provision, erosion control, and flooding reduction, depending on both infiltration and ET. However, it is still difficult to state a general conclusion about ET responses due to the significant lack of supplementary information (e.g., soil properties) in the published literature and specially, due to the absence of studies from the tropics. How the interaction of the very different environmental attributes (e.g., type of soil and climate) affects the response to the hydrological changes due to the replacement of grasslands remains to be explored.

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