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Évaluation et modélisation de l'érosion du sol sous différentes pratiques de conservation sur les plantations de café ombragées sur les terres de pente (Ultisols)

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Résumé

L'objectif principal de ce travail était de mieux comprendre les processus et la dynamique d'érosion des sols sur pentes raides sous culture permanente (café sous arbres d’ombrage). Nous avons aussi examiné l’influence de quelques pratiques culturales typiques à l'échelle des parcelles de café sur l'intensité de l'érosion. Nous avons enfin mesuré le ruissellement et l'érosion à l'échelle du petit bassin versant pour évaluer l'impact sur les services écosystémiques comme la fourniture d'eau de qualité, pour la production d'énergie ou pour la consommation humaine.

Huit parcelles expérimentales ont été installées dans une plantation de café avec une pente moyenne de 65 % avec *Erythrina* sp. comme arbre d'ombrage. Le ruissellement superficiel a été mesuré chaque 5 min et collecté pour la mesure de la concentration en sédiments et l'évaluation de l’érosion.

La pluviométrie annuelle a été de 2206, 1778 et 2220 mm en 2011, 2012 et 2013 respectivement avec une alternance marquée de saison sèche et saison des pluies. La lame ruisselée totale a été en moyenne de 103, 54 et 33 mm respectivement pour les trois années. La concentration moyenne en sédiments a été d’environ 1.3 g l^{-1} avec des variations temporelles réduites entre événements pluvieux et entre années. La perte de sol annuelle moyenne a diminué de 1.69 à 0.91 puis 0.58 t ha^{-1} an^{-1} de 2011 à 2013. La dynamique temporelle a été analysée à trois échelles de temps : annuel-mensuel, événement et intra-événement. Environ 60% de la pluie et 90% du ruissellement et de l'érosion s’est produit pendant les périodes d'aout à octobre, dont plus de la moitié en octobre. La hauteur de pluie de chaque événement et la teneur en d'eau du sol ont expliqué l’essentiel de la variabilité du ruissellement et de la perte en terre. Le stockage d'eau de sol hérité de l'année précédente a joué un rôle important sur le ruissellement. Un modèle d'infiltration simple (Diskin et Nazimov) a été utilisé pour évaluer la hauteur de ruissellement pendant une pluie: une combinaison de l’intensité moyenne de la pluie et de la teneur en eau du sol explique correctement les différences observées pour le ruissellement et la perte en terre à une échelle inter-événement.

En 2012 quatre traitements ont été appliqués avec deux répétitions chacun : 1. traitement de référence avec renouvellement de mini-terrasses et désherbage manuel ; 2. idem 1 sans renouvellement de mini-terrasses ; 3. idem 1 sauf désherbage avec un herbicide ; 4. idem 1 avec taille réduite des arbres d'ombrage. On a considéré trois périodes : P1 avant application des traitements, P2 les deux mois suivants traitement et P3 l'année suivante (2013). Les différences significatives entre les ratios de traitements/référence pour les trois périodes indiquent une augmentation du ruissellement et de la concentration en sédiments après renouvellement des mini-terrasses avec un effet toujours présent pour P3. Le désherbage avec un herbicide n'a pas montré d’influence claire. Le traitement avec taille réduite des arbres d'ombrage a réduit l'érosion pour les conditions d'humidité de sol > 30 % seulement.

Le ruissellement superficiel, la concentration en sédiments et la perte en terre ont été mesurés à l’exutoire d’un petit bassin versant (31 ha, de pente moyenne de 60 %) en 2012 et 2013. Seules les pluies de hauteur supérieure à 5 mm (169 événements) ont produit du ruissellement et l’essentiel des volumes ruisselés a été produit lors des fortes averses (> 40 mm). Les coefficients de ruissellement ont été faibles (0.9 %) aux deux échelles en 2013. Ils ont atteint 2.44 % pour les parcelles et 0.9 % pour le bassin versant en 2012. L’écoulement de base était également faible pour le bassin versant (13-16 % de la pluie totale) avec une grande partie de la pluie (environ 20 %) perdue par percolation. La concentration moyenne en sédiments a été d’environ 1.65 g l^{-1} à l’échelle de la parcelle avec des valeurs maximales de 5.64 g l^{-1}. La concentration moyenne en sédiments à l'échelle du bassin versant a été de 0.51 g l^{-1}. La perte de sol annuelle a été de 0.73 et 0.36 t ha^{-1} an^{-1} à l’échelle parcellaire (tous traitements confondus) pour 2012 et 2013 respectivement et de 0.46 et 1.24 t ha^{-1} yr^{-1} à l’échelle du bassin versant pour les mêmes années.

Le système de culture du café sur pente raide avec arbres d’ombrage étudié a présenté une perte en terre modérée comparée à l'érosion potentielle qui pourrait arriver dans des environnements semblables avec une protection de la surface du sol par la végétation moins importante. Il semble donc contribuer à fournir des services environnementaux de valeur en terme de recharge des aquifères et de réduction des apports de sédiments aux cours d’eau.

Mots clés:

L'érosion des sols, le ruissellement superficiel, Diskin et Nazimov le modèle d'infiltration, l'intrigue de ruissellement, le désherbage mécanique, herbicide, terrasses, l'ombre d'élagage, des bassins versants, le budget de l'eau

Abstract

The main objective of this work was to better understand soil erosion processes and dynamics on steep lands cultivated with a permanent crop (shade coffee). We also investigated the effect of some typical coffee practices on field scale erosion intensity. Finally, we measured runoff and erosion at watershed scale to address their impact on ecosystem services such as quality water provisioning, either for energy production or for human consumption.

Eight large experimental plots were installed in a 65% average slope coffee plantation with *Erythrina sp*. as shade tree. The superficial runoff was measured every 5 min. and collected for sediment concentration measurement and soil loss assessment.

Rainfall depth was 2206, 1778 and 2220 mm in 2011, 2012 and 2013 respectively with a marked succession of dry season and rainy season. Total runoff was 103, 54 and 33 mm along those three years. Annual average sediment concentration at plot scale was about 1.3 g l^{-1} with reduced temporal variations between years or rainfall events. The plots' average annual soil loss (under normal management) decreased from 1.69 to 0.91 and 0.58 t ha^{-1} from 2011 to 2013. An analysis of the temporal dynamics was performed in three time scales: annual-monthly, event and intra-event. Around 60% of rainfall and 90% of runoff and soil loss occurred each year during the August-October periods and more than half of it in October. Total event rainfall and soil water content explained most of surface runoff and soil loss dynamics, while inherited soil water storage from previous year played an important role on the relationship between rainfall and runoff dynamics in the following year. A simple infiltration model (Diskin and Nazimov) was used to estimate runoff during a rainfall event: a combination of rainfall intensity and soil water content dynamics on an intra-event scale explained correctly the differences observed in runoff and soil loss on an inter-event scale.

In 2012 four treatments were applied with two replicates each: no mini-terraces renewal, weed control with herbicide, reduced pruning pressure on shade trees and reference management. Three periods were considered: P1 before treatment application, P2 the next two months afterwards and P3 the year after (2013). The significant differences between treatments/reference ratios for the three periods suggested higher runoff and sediment concentration when mini-terraces were renewed and the effect decreased but was still present in P3. Chemical weed control did not show a clear trend. The reduced pruning treatment reduced erosion only for superficial soil moisture >30%.

Superficial runoff, average sediment concentration and soil loss were monitored at the outlet of a small watershed (31 ha, 60% average slope) during 2012 and 2013. Rainfall events greater than 5 mm (169 events) produced runoff at both scales and most of runoff amount was produced for strong rainfalls (> 40 mm). The runoff coefficients were very low (0.9%) at both scales in 2013. But it was 2.44% for plots and 0.9% for watershed in 2012. The base flow was also very low on this watershed (13-16% of total rainfall) with a large part of the rainfall (about 20%) being lost by percolation. The average sediment concentration at the plots was about 1.65 g l^{-1} and the maximum value was 5.64 g l^{-1}. The average sediment concentration at watershed scale was 0.51 g l^{-1}. Estimated annual soil losse were 0.73 and 0.36 t ha^{-1} yr^{-1} at plots scale (all managements included) for 2012 and 2013 respectively and 0.46 and 1.24 t ha^{-1} yr^{-1} at watershed scale for the same years.

The shade coffee system studied on steep land showed a tolerable soil loss compared to the potential erosion that could occur in similar environments with less vegetal surface protection. It could offer valuable environmental services in term of aquifer recharge and low sediment contribution to streams.

Keywords:

Soil erosion, superficial runoff, Diskin and Nazimov infiltration model, runoff plot, mechanical weed control, herbicide, terraces, shade pruning, watershed, water budget.

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Foreword

Soil erosion is a term usually associated with negative consequences for the environment, both on-site and off-site. On-site, it degrades soil quality, reduces soil thickness and water storage capacity. In the case if off-site impacts, it is source of sediments and responsible of siltation of reservoirs or dams; it is also associated with hydro-morphological modification of riverbeds (hydraulic capacity reduction) and with road and infrastructure damages. However, soil erosion may also contribute to formation of productive low lands from deposition of fertile sediments. The latter implies that not all impacts associated with erosion are negative; this process can also have positive outcomes under specific circumstances.

A clear sign of soil erosion is browned rivers due to suspension of sediments from watersheds. However, incomplete knowledge of the spatial origin of the sediment generally prevails. It is assumed that crop areas are the main sources of sediments. This assumption is too coarse to allow for evidence-based decision making to correct for the problem and thus reduce erosion. Deeper knowledge of the complete erosion process is required, for example on the origin of sediments, their fate along their transport, possible land use and management practices that could effectively reduce it since most of these variables are site specific (they vary greatly in response to land slope, soil type, climate) local studies are required, including in situ measurements.

Soil erosion is not only complex but also extremely variable in time and space. Although it has been widely studied around the world, there are still information knowledge gaps to be filled. For example research of soil erosion on steep lands is still limited compared with studies on moderately sloped lands. Furthermore, the erosion processes involved on steep lands could be quite different as expected under specific production systems. .

Coffee cultivation on steep land is a potential source of sediments. However, shade coffee systems also referred as AgroForestry Systems are supposed to be more “environmentally friendly”, and less prone to erosion because of “additional protection against rainfall and runoff by aerial vegetation and roots”. This appraisal comes from the fact that from a system perspective, agroforestry plantations are closer to a forest system. Forests are frequently used as base line to estimate minimal soil loss in a stable system.

Coffee plantations however, are not all similar in terms of plant distribution, land slope, sunlight orientation, soil type and management. It could be argued that some shade coffee systems are very stable in terms of soil degradation even if located on steep lands. After all, those systems have been present for decades and would be depleted by now if soil erosion rates had been as high as previously reported. This overestimation of soil loss from coffee systems is probably due to an incomplete understanding of the erosion process over time.

If it is proven that some land uses and management practices decrease off-site erosion effects –on top of on-site, privatively owned advantages-, then producers should be encouraged for adopting them.

All these questions motivated the research presented in this thesis.

Chapter 1: General introduction and literature review

1.1 Scientific context and main issues

Erosion is a natural process of landscape changes that have taken place over millions of years. The natural erosion process is relatively slow and speeds up as human intervention unbalances the system (Lal, 2007). These interventions are forced by the increase in food demand, which creates more pressure to produce on lands with low agricultural potential it degraded lands (Lal, 1990; Morgan, 2005; Sidle, 2006). Land use change from forest to crops causes a high increase on superficial runoff due to reduction in macroporosity, less soil coverage (litter) and canopy coverage (Hairiah et al., 2004, Widianto et al., 2004). The natural and highly stable soil system permanently covered by plants is disrupted. Soil erosion accelerates as soil coverage diminishes after this change.

Soil erosion and conservation has been an interest since the 1920´s in the United States and since the 1970´s in Western Europe (Morgan, 2005). However, soil erosion had been observed centuries ago. Plato, for example, in the unfinished dialogue Critias, refers to the problems of deforestation, soil erosion, and the drying up of springs (Rapidel and Le Coq, 2014).

First studies on erosion on soil slope occurred at the beginning of the 1940´s (Wischmeier and Smith, 1978). Zingg (1940) measured soil erosion with simulated rain on 20% soil slope and different plot lengths; Smith and Whitt (1947, cited by Liu et al., 1994) measured similarly to Zingg but on soils with slightly lower slope. In 1957 Smith and Wischmeier reported soil erosion from plots and in 1978 the guide for USLE (Universal Soil Loss Equation) was published (Wischmeier and Smith, 1978) based on plot data from the United States and after years of calibration of their factors. This USLE has been used widely all around the world despite its creators' advice that it was calibrated for a specific zone (Wischmeier, 1976).

Soil erosion increases with slope, steep lands being also often associated with fragile lands when cultivated (Lal, 1988). The fact is that, even when they have been considered marginal and not appropriate for agriculture, an important extension of these steep lands (in the tropical zone) has been used for agriculture for centuries (for example: in China, Thailand, Philippines, Colombia and Central America). Some crops such as Arabica coffee produce grains of better quality (hard bean) at higher altitudes (500-1800 m.a.s.l.) where steep slopes dominate the landscape.

Research on soil erosion on steep lands is relatively new (Konz et al., 2010) and as a result, the process has not been investigated as much as in low-moderate slopes (Liu et al., 2000; Janeau et al., 2003; Lopes et al, 2002). In the tropics, due to high pressure on land for agricultural uses, steep soils under agricultural production are common. The option to stop producing on these lands is no longer practical, since numerous families have developed a large dependency upon them and do not have suitable alternatives for their livelihoods (Lal, 1988; Lal, 2014). In order to come up with possible solutions to the erosion challenge, the processes involved on those steep-land erosion systems need to be better understood.

In Costa Rica, coffee is one of the most developed agricultural crops and coffee plantations are present in the main basins used for hydroelectrical generation, which are affected by soil erosion and sedimentation in dam reservoirs (Gómez-Delgado et al., 2011).

Producers under these extreme agricultural conditions might improve their productive systems if encouraged by incentives (monetary or in services). The main incentive should be preserving their highly valuable soil asset. There are also offsite benefits from protecting soils under coffee cultivation, such as aquifer protection and recharge, less superficial water contamination by soil particles and pesticides and better quality water streams (De Jesus, 2015), less siltation in dam reservoirs (Gómez-Delgado et al., 2011; Solano, 2010), less riverbed increases and infrastructural damages due to flooding.

An example of monetary incentives is the Costa Rican payment for environmental services (PES) Program PES started in 1997 and has evolved to include agroforestry systems (Pagiola, 2006) such as shade coffee plantations.[1]

A study under a shade coffee plantation on a medium slope (<20%) was carried out by Gómez-Delgado et al. (2011) on one of the largest coffee farms in Costa Rica located in Turrialba. One of the contributions of their study was information to support payment for hydrological services (PHS), which is a component of CR`s PES Program. However, in order to assess how much the service should be compensated, a better understanding and measuring of the erosion process, including steep slopes is needed.

1.2 Runoff and erosion factors and processes on cultivated tropical steep lands

Runoff and soil erosion result from the interaction of four categories of factors: rainfall characteristics, soil properties, topography and land use/land cover (Wischmeier & Smith, 1978; Morgan, 2005). The soil erosion process is not continuous during a rainfall event or during a rainy season, and depends on initial conditions, such as soil water content (Truman and Bradford, 1993; Wei et al., 2007), soil ground and vegetation cover (Paningbatan et al. 1995; Truman et al., 2005), soil hydraulic properties, soil roughness and crusting (Descheemaeker et al., 2006; SCS, 1972; Le Bissonnais and Singer, 1992;

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[1] The most common shade trees used in Costa Rica are *Erythrina poeppigiana, Erythrina glauca, Inga edulis, Inga vera, Inga mollifoliola, Inga paterno, Eucalyptus deglupta, Cordia alliodora, Persea sp. and Musa sp*.

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Ribolzi et al., 2011). Some of these factors have been analyzed in different studies on steep soils (Presbitero et al., 1995; Janeau et al., 2003; Valentin et al., 2008; Thomaz, 2009). These factors and resulting processes will be analyzed below.

The rainfall characteristics that usually have high correlation with superficial runoff and soil erosion are: depth, intensity, duration and kinetic energy (Vacca et al., 2000; Gomi et al., 2008; Ghahramani and Ishikawa, 2013). Rainfall depth, intensity and duration are essentially related to runoff production: when rains fall with an intensity that is higher than soil surface infiltration rate, the rainfall in excess runs off. This can be achieved due to the soil's surface characteristics, or if the rainfall is abundant, because of water logging in deeper layers that gets up to the surface. Rainfall kinetic energy relates to the capacity to detach sediments from the soil's surface and produce soil erosion.

The most evident factor for runoff production is rainfall intensity. Zhu and Zhu (2014) found that rainfall intensities higher than 12 mm h^{-1} produced runoff. Khamsouk et al. (2002) worked in Tumbaco and Mojanda (Ecuador) where according to De Noni et al. (1990, 2001) around 80% of soil loss was due to specific rain fall events between 40 to 80 mm h^{-1} and 40 to 60 mm h^{-1} for Tumbaco and Mojanda respectively. Depending on the soil surface, runoff can be produced at low rainfall intensity: Le Bissonnais et al. (1998) measured runoff production at watershed scale for 1 mm h^{-1}. Tropical rainfalls are known for their high intensities (Vahrson et al., 1992; Patin et al., 2012).

Rainfall depth is frequently related to runoff and soil erosion processes. Descheemaeker et al. (2006) measured rainfall thresholds on a daily basis between 3 to 20 mm in order to obtain superficial runoffs lower on humid areas compared with semi-arid areas. Thomaz (2009) found that rainfall events greater than 30 mm depth were the most important in terms of superficial runoff and soil loss production. But deep rainfall events are not necessarily always associated with high runoff production (Nearing et al., 1999). High rainfall accumulation can drive high runoff and soil loss depending on the temporal dynamics of other factors (Le Bissonnais et al., 1998). For example, according to Chaplot et al. (2005), in summer, intense rainfall may cause a high runoff depth and peak flow on a dry soil.

The rainfall kinetic energy has an important role in soil detachment process, and it positively affects interrill and splash soil erosion. Zhou et al. (2013) measured on Ultisol soil samples (0.5 m x 0.5 m) low and high kinetics energy effect on runoff production, crusting and infiltration. The low kinetic energy test had higher infiltration rate, which corresponded to a lower runoff production. They also observed that Ultisols are prone to crusting if coverage is low. The kinetic energy that rainfall drops carry out will act according to the surface gradient and rainfall direction. On steep soil the vertical component of this kinetic energy can be cancelled out partially and effects such as soil crusting and soil compaction could be less than those on gentler slopes (Janeau et al., 2003).

In addition to rainfall characteristics, soil properties are essential factors in determining runoff and erosion. Soil infiltration rates influence runoff production; aggregate stability decrease soil's ability to crust at the surface, and will also decrease the detachment of soil particles that could be taken away in the runoff flow. (Wang et al., 2014)

Infiltration rate varies as the soil water content changes in an inverse relationship since it approaches to hydraulic conductivity under soil water saturation. In this sense, the more that water infiltrates into the soil, the less runoff is produced and thus less soil loss occurs. There is a simple but practical infiltration model presented by Diskin and Nazimov (1995, 1996) that estimates soil infiltration and runoff (by difference) from rainfall data at different time records. It becomes useful to complement rainfall data per event and gets an approximation of potential runoff, which at the end is the main component of soil erosion estimation.

On the other hand, infiltration is also affected by soil crusting, which impedes the entrance of water into the superficial soil's profile, augmenting runoff. Patin et al. (2012) determined at plot and watershed scale that soil crusting was the main factor associated with rainfall infiltration. This crusting is also promoted by poorly covered soil exposed to the impact of rainfall drops, which redistributes fine particles; by small pores being sealed and also due to low biological activity (Podwojewski et al., 2008). On experimental plots with simulated rainfall and crusting, it was demonstrated that rainfall kinetic energy was a major driver for structural and sedimentary crusting (Zhou et al., 2013). A good alternative to impede crusting formation would be mulching and good soil coverage (Xu et al., 2013).

The soil's strength resistance to be disaggregated plays another important factor to prevent soil detachment and loss. Thus soil's erodibility is intrinsically associated to this characteristic. Le Bissonnais (1996) developed the base methodology (LB method) for measuring this soil characteristic. The LB method has been modified (Yan et al., 2008) for prediction of interrill (or laminar) soil loss with good results after the validation of the model that incorporated it. Shi et al. (2010) also used the LB method for developing an instability index with good validation results too. These applications reinforced the importance of aggregate stability on soil erosion. Wang et al. (2014) used this aggregate stability as a baseline estimation of relative mechanical breakdown index, which had high correlation with soil particles' abrasion and sizes after different length transportation tests. Also this variable is associated to resistance to landslides (Nespoulous, 2011).

It is classically thought that soil slope does influence runoff production and increases erosion due to higher flow velocity and therefore turbulence (Sánchez, 1976; Konz et al., 2010; Wischmeier and Smith, 1978). Runoff actually gets higher under steep slopes: greater runoff as the slope increased was observed by Fox et al. (1997), Chaplot and Le Bissonnais (2000), Khamsouk et al. (2002), Cheng et al. (2008), Yan et al. (2008), Essig et al. (2009), Shi et al. (2010) and Patin et al. (2012). The explanation for these observations could be related to a decrease in the infiltration rate due to a lower overland flow depth and therefore less ponding pressure head (Fox et al. 1997).

Other studies have found lower runoff on steep slopes, for various reasons (Assouline and Ben-Hur, 2006; Descheemaeker et al., 2006; Ribolzi, 2011): a) a lower raindrop density per unit of surface area in steep slopes, which reduces the effectiveness of rainfall intensity -estimated as the vertical rain intensity multiplied by cos α where α is the soil slope angle (Rudolph et al. 1997; Patin et al. 2012); less formation of soil crusting (Valentin and Bresson, 1992; Janeau et al., 2003; Patin et al., 2012) and b) less time in finding preferential paths to cracks or depressions with high infiltration properties whose spatial distribution is likely to be heterogeneous in the field (Gomi et al., 2008; Patin et al., 2012).

Inverse effects of soil slopes on runoff and erosion were also reported. Khamsouk et al. (2002) using soil erosion plots in Martinique and Ecuador observed that runoff concentrated in rills and gullies when slope was higher than 15-20%. They found that runoff decreased as slope increased (on bare soil) but soil erosion got larger. The higher the slope (10 to 40%) the soil erosion changes from sheet and rill erosion to rill and creep erosion. The inverse relationship between soil slope and runoff was also reported by Heusch (1971) and Poesen (1984, 1994) both cited by Khamsouk et al. (2002). Govers (1990, cited by Khamsouk et al. 2002) tried to explain this phenomenon by "differential superficial soil cracking on steep slopes". Ribolzi et al. (2011) observed -in a detailed study with infiltration measurements- less runoff, but also less erosion (due to less crust and low detachment) on steep land (75%) compared to a 30% slope. These results show how "the higher the slope the lower the erosion rate with higher infiltration rate". This phenomenon is explained due to more pervious and less erodible micro terraces on the 75% slope gradient. Janeau et al. (2003) found a similar trend in northern of Thailand on gravely loamy soil and a convex hill. They used fifteen 1 m^2 replicate plots and different slope gradients from 16 to 63%. They got a clear negative relationship (R^2=0.66 each) between slope gradient and runoff, soil detachment and sediment concentration. Furthermore, from their results the final infiltration rate increased as the slope gradient increased as well.

Other studies showed threshold effects of slope on erosion: Fu et al. (2011) analyzed the splash loss from a constantly simulated rainfall (67 mm/h) on different slope gradients (9, 18, 27, 36, 47, 58, 70, 84 and 100%) using small plots. They found that the total splash loss increased as the soil slope increased but up to a maximum value and then it started to decrease. On the other hand, Van Dijk (2005) affirmed that splash loss decreased as the plot size increased and that it became zero when the plot length reached 10-meter length. Liu et al. (1994, 2004) studied the effect of slope gradient on soil erosion and later on they studied the effect of plot length (Liu et al. 2000) always on the empirical results from the USLE and RUSLE. Based on their results (and USLE/RUSLE calibrations) the effect of increasing the soil gradient is not linear but quadratic at least until 50% slope is reached.

These contradictory results may be due to complex interactions between the slope gradient and other factors influencing infiltration, runoff and erosion, such as soil characteristics (crusting as mentioned before, macroporosity, soil texture, infiltration capacity), vegetation cover (Anikwe et al., 2007) and soil water content (Dunne et al., 1991; Peugeot et al., 1997; Wei et al., 2007).

Land cover is supposed to reduce the rainfall kinetic energy, particularly if this cover is close to the soil's surface, and introduces physical obstacles to surface water flow, decreasing its energy. Steep lands in tropical areas may be very susceptible to soil erosion after removal of natural vegetation due to their rough topography and erosive climate (Lal, 1985; Dadson et al., 2003; Widianto et al., 2004; Xu et al., 2013).

Many studies have found increased runoff as the soil coverage decreases (Descheemaeker, 2006; Thomaz, 2009; Xu et al., 2013; Zhu, 2014). Descheemaeker et al. (2006) measuring superficial runoff from small plots (10 m^2) found the vegetation coverage explained 80% of variation in superficial runoff through an exponential decay function where runoff became negligible as soil coverage was greater than 65% (also determined by Blanco and Aguilar (2015)). Northcliff et al. (1990) found that soil coverage greater than 30% also provided enough protection to the soil so that superficial runoff became very low. This drop in superficial runoff was attributed to vegetation that improved soil infiltration. Mohammad & Mohammad (2010) also found a significant change in water runoff and sediment loss under different soil coverages. In fact, when natural vegetation (mainly by the shrub *Sarcopoterium spinosum*) and forest were tested, the runoff was very low compared with cultivated land, deforestation and natural vegetation with *s. spinosum* removal. Soil coverage is also associated reducing sediment concentrations (Huang et al., 2001; Poulenard et al., 2001; Podwojewski 2008; Konz et al., 2010). Blanco and Aguilar (2015) determined that soil slope explained (4%) less erosion variability than litter layer coverage (66%). In Germany, Hacisalihoglu (2007) using data from one year period found on vineyards, on grazed grasslands, regeneration areas, scattered shrubs and forest areas up to 50% slope that the areas with plant coverage had around six times less soil erosion compared to areas with no plant coverage. Soil erosion increases when low or none coverage is present (Labrière et al., 2015) and high intensity rains occur which is easily found in the Tropics. Khamsouk et al. (2002) in Martinique and

Ecuador with up to 40% slope soil found that if the surface is covered by mulch (crop residues) then runoff and soil erosion decreased drastically. Widianto et al. (2004) and Hairiah et al. (2004) found similar results in terms of soil coverage.

The effect of coverage is not limited to rainfall interception, but also plant roots penetration improving soil porosity (Dariah et al., 2004; Gyssels et al., 2005; Hairiah et al., 2006) and soil organic matter content which improves soil structure (Casermeeiro et al., 2004) and increases infiltration capacity (Paningbatan et al., 1995; Mohammad and Mohammad, 2010). All those improvements led to less soil detachment thus soil loss dropped (Podwojewski et al., 2008).

Terraces (or pseudo terraces) are a common practice in coffee plantation on steep lands. Terraces decreased most of the superficial runoff compared with cropland under rainfall events greater than 10 years recurrence interval (Paningbatan et al., 1995; Zhu and Zhu, 2014) and Kothyari et al. (2004) measured very low runoff and soil loss (0.06-0.42 t ha^{-1} yr^{-1}) in small terraces system in India on rainfed agriculture with 41.4% soil slope and 75% surface coverage.

1.2.1 Scale factor

Scale is a very important factor on runoff and erosion measurement. The differences observed across scales can be related to changes in the basic processes involved, in the inclusion of land uses of different natures, as well as being the result of the increased variability in the parameters as the scales increase. Contradictory factors are at play and can have contrasting effects: as the area increases, some water flows can re-infiltrate in the surface, but subsurface flows can also emerge as water sources. Sediments in suspension can be deposited in areas where water flows slowly down.

There is no consistency in standard runoff plot size, dimensions and construction rules for the measurement and evaluation of soil erosion at field scale. Plot sizes in studies are from 1 m^2 (Harmand et al., 2007; Podwojewski et al., 2008; Valentin et al. 2008; Patin et al., 2012) up to 1000 m^2 (Gómez-Delgado, 2010). Morgan (2005) recommends 10 m plot length at least which is fulfilled by USLE (Universal Soil Loss Equation, Wischmeier (1960)) erosion plots established all over United States of America and Puerto Rico.

In terms of rainfall characteristics in a watershed, a high spatial variability could explain more the sediment export than the splash erosivity, rainfall intensity and its energy (Descroix et al., 2001). Many studies did not have the chance to monitor rainfall variability across the watershed due to having only one weather station or just one close to the study site (or even one not so close to the site). In fact, it would be fair enough to expect that the larger the study area, the larger the spatial variability in rainfall distribution. This variability also includes soil lithology (Descroix et al., 2002). Descroix et al. (2001)

observed two different rainfall intensity thresholds for runoff production, 2 and 14 mm h^{-1}, at watershed and plot scales respectively which was influenced by ignimbrite presence under soil. A similar trend was observed with tuffs and conglomerates where runoff started at 6 and 18 mm h^{-1} for watershed and plot scales respectively too. These types of spatial variability effects should be taken into account when an up-scaling from plot to watershed area is attempted.

Soil erosion rates vary from small plots to large scales (watersheds) under the same weather conditions (Cerdan et al. 2004; De Vente et al. 2007). The trend could go either way; the erosion rate could increase as the study area increases (Verbist et al., 2010) or inversely (De Vente and Poessen, 2005; Descroix et al., 2008). There are many factors affecting these changes such as lithology, soil surface features, hydraulic conductivity (Descroix et al., 2002; Verbist et al., 2010), infiltration changes under different slopes (Zhu and Zhu, 2014), large exchange of surface water between catchments (Chappell et al., 2004), overland flow pattern, soil sealing stages, rates of soil coverage (Descheemaeker et al., 2006; Blanco y Aguilar, 2015), natural and human pathways (Ziegler and Giambelluca, 1997; Cerdan et al., 2004), gullies, linear erosion, rill erosion (Chaplot et al., 2005), spatial heterogeneity in land use (Valentin et al., 2008, Le Bissonnais et al., 1998), land slides and river banks erosion (Verbist et al., 2010).

A common reported source of high runoff rates at watershed scale are roads and human pathways driving high erosion rates (Ziegler and Giambelluca, 1997; Rijsdijk et al., 2007; Verbist et al., 2010; Collins et al., 2012). Gómez-Delgado et al. (2010) found roads that covered 4.5% (represented as 10 km road length) of a 90 ha watershed as one of the main sources of runoff. Ziegler et al. (2004) measured 80% of road runoff that could become a good source of high flow runoff into plantations. Research on the mechanisms and intensity of soil erosion on steep slopes is still limited and progress needs to be made in order to estimate the rate of erosion in steep coffee plantations under tropical conditions, and the possible mitigation measures that might help in reducing it.

1.3 Specific knowledge about soil erosion on coffee crops

Coffee crops are produced in tropical countries such as Costa Rica, Colombia, Philippines, México, Guatemala, Honduras, Uganda and Vietnam among others. Costa Rica is the 13th main exported of coffee (ECF 2014). The activity is an important income source for families, both for producers and for temporary workers in farms.

Studies on soil erosion for coffee (*Coffea arabica*) are limited. Most of those studies have been on soil slopes of over 20% (Table 1.1). When coffee crops are on steep lands one could expect high soil loss rates due to high runoff potential. However, the practices of maintaining coffee alleys clean of weed or any kind of live coverage are not common

(Presbitero et al., 1995). Even more, litter layer increases (Bermúdez, 1980; Ataroff and Monasterio, 1993) as coffee crop gets older than 3 years and runoff decreases so soil erosion diminishes, getting close to forest rates (Ataroff and Monasterio, 1997; Dariah et al., 2004; Widianto et al., 2004; Hairiah et al., 2006).

Coffee cropping systems on steep lands could be prompted to high rates of runoff and soil erosion with not just on-site effects, but also with significant off-site effects related to the transfer of sediments and associated pollutants (Sidle, 2006; Verbist, 2010; Cannavo 2011; Blake et al., 2012). However, different coffee practices could be modified to reduce water runoff and sediment concentration and thus soil erosion (Paningbatan et al., 1995; Descheemaeker et al., 2006). There are studies where changes in crop management have had significant changes in superficial runoff and soil loss (Presbitero, 1995; Thomaz, 2009; Valentin et al., 2014).

A comparison from different soil erosion studies on coffee systems would lead to a better perception of what has been achieved and what is still open to research. Table 1.1 summarizes the runoff and erosion studies in coffee found in the literature, and shows how different soils were used; from relatively new formation soils such as Inceptisols up to more developed ones in terms of structure such as Alfisols and Ultisols whereas soils with particular structure (allowing high infiltration capacity if crusting is not present and good macro porosity status) and texture (medium to gross particles) that provide good infiltration capacities as the case of volcanic soils (Andisols). The latter was observed in Gómez-Delgado (2010) and helped with low runoff production.

The plot sizes varied from 1 m^2 up to 1000 m^2 with median plot sizes around 100 m^2. This heterogeneity in plot size was also combined with different study periods, from 3 months (Widianto et al., 2004) up to 5 years (Ataroff and Monasterio, 1997; Iijima et al., 2003). Prior any runoff measurements it is reasonable to expect differences among plot sites because soil types and weather conditions vary. However, the low soil loss and runoff coefficients are relatively consistent in shade coffee systems. Sun coffee systems (without shade trees) always have higher erosion rates than shade coffee systems. Furthermore, there is no consistent trend of the effect of plot size on runoff or erosion. From all reported studies none of them had continued time monitoring of runoff and rainfall, where Gómez-Delgado et al. (2010) were the closest, to that detailed analysis with a runoff continuous time control, but they were focused more in hydrology modeling.

From Table 1.1 few studies measured sediment concentration at plots and watershed. The values were relatively low compared with other studies on different crop systems. However, the studies that reported high soil loss (Afandi et al., 2002; Iijima et al., 2003; Dariah et al., 2004 and Widianto et al., 2004) did not reported sediment concentrations where the explanation for those high soil loss rates could be related to high sediment concentration since reported runoff was low.

A good complementary study to this group will be an assessment of runoff and sediment concentration in continuous time under two scales (plot and watershed) simultaneously which is one of the component of our research.

Table 1.1. Summary of soil erosion studies reported in the literature for lands under coffee plantation (at least one of the treatments). Sources are ordered by published year.

Source	Widianto et al. 2004	Dariah et al. 2004	Iijima et al. 2003	Afandi et al. 2002	Ataroff and Monasterio 1997	Vahrson & Cervantes 1991	Bermúdez 1980
Country	Indonesia	Indonesia	Indonesia	Indonesia	Venezuela	Costa Rica	Costa Rica
Slope (%)	58	50-60	27	27	60	60	30
Soil type	Volcanic influence	Oxic Dystrudepts	Vertic Dystrudepts	Vertic Dystrudepts	Typic Humitropept	Udic Haplustalf	Typic Dystropepts
Method	4x10 m	8x15 m	3 replicates; 12 plots: 108 m2	5 x 20 m plots	6x2 m plots. No repetition	7 x 22.1 m plots	4x10 m
Time period	May-July 2001	Nov. 2001-July 2003	1995-1999	2000-2002	1988-1992	1990	1979 (July-Dec.)
Land use	Sun coffee: 1, 3, 7 and 10 yr old	Sun coffee and shade coffee; + *Gliricidia*, trenchs, hedgerows.	1 yr old coffee plants planted in 1995. Associated with vegetable crops	Shade coffee and different weeds treatments	Shade coffee and sun coffee	Shade coffee and sun coffee	-Coffee + *Erythrina poepiggiana* - Coffee + *Erythrina sp.* + *Cordia alliodora* - Sun coffee
Soil loss (t ha^{-1} yr^{-1})		0.3, 33.6, 37.2, 7.1 and 6.8 for forest, 1, 3, 7 and 10 years old coffee plantation.	2.6 to 7.3	4.8 to 23	0.39 to 6.62	0.17 and 1.36 for sun coffee and shade coffee	No reported
Annual runoff (%)	27, 75, 134, 67 and 85 mm for forest, 1, 3, 7 and 10 years old coffee plantation.	Not measured	Not measured	Max. 1.5%	Max. 8.3% in 15 days period	0.6 and 1.3 for sun coffee and shade coffee	1.36 +- 0.51 2.07 +- 0.91 1.44 +- 0.62
[Sediment concentration] g l^{-1}	Not reported	Not reported	Not reported	Not reported	Not reported	I Not reported	0.48 0.71 3.47

Table 1.1. (Cont.) Summary of soil erosion studies reported in the literature for lands under coffee plantation (at least one of the treatment
Sources are ordered by published year.

Source	Cannavo et al. 2011	Solano, S. 2010	Verbist et al. 2010	Gómez-Delgado 2010	Thomaz 2009	Siles et al. 2007	Harmand et al. 2007
Country	Costa Rica	Costa Rica	Sumatra	Costa Rica	Brazil	Costa Rica	Costa Rica
Slope (%)	<5	30-60	40-58	20	62.5		
Soil type	Dystric Haplustands	Not available	Andosol	Andosol	Regosol	Dystric Haplustands	Ustic Paleumults
Method	1 m^2	5 x 20 m plots aprox.	Plots: 4 x 10 m 8 x 15 m	90 ha watershed and 14x72 m plot	2 x 1 m plots with 3 replic. Gerlach trough to 100 l drums	1 m^2	1x1 m^2
Time period	2004-2005	2009	2005-2007	2008-2009	2003-2004	2006	Feb. 2002-Apr. 2003
Land use	Shade coffee with *Inga densifloria* Sun coffee	Shade coffee at plot and watershed scale (>80% area)	Suncoffee and shade coffee	Shade coffe	Burned site, fallow site and shrubs cover	AF: shade coffee with *I. densiflora* MC: sun coffee	4-10 years old. Sun coffee and shade coffee with *Eucalypt deglupta*
Soil loss (t ha^{-1} yr^{-1})	Not estimated	Plots: 10.9 and 21.8 (428 ha watershed)	Sun coffee: 4-11 Shade coffee: 1.8 Watershed SY 3-10 times > than plots	9 months Plot: 0.01 Watershed: 1.0	6.12, 5.10 & 1.18 (May to April)	No measured	No measured. Estimated < 3 base o runoff
Annual runoff (%)	Shade coffee: 5.4 Sun coffee: 8.4	Not measured	Suncoffee: 10-15 Shade coffee: 4-7	Max. in plots: 0.1 and 0.2 for shade coffee and sun coffee	2.4, 1, 1.4 (May to April)	Runoff under AF was half of MC	Sun coffee: 2 Shade coffee: 3
[Sediment concentration] g l^{-1}	Not measured	Not measured	Watershed, máx.: 5.0	Flume: Mean: 0.05 Max: 0.89	NA	Not measured	Not measured

1.4 Objectives and plan of the thesis

Looking for a better understanding of soil erosion dynamics on steep slopes and a permanent crop (shade coffee as an agroforestry system), the analysis started with runoff and erosion monitoring under natural rainfall on replicated large experimental plots installed in a farmer's cultivated field without any treatment applications. The idea was to observe and analyze soil's natural status behavior under erosion processes. Then, in order to determine effectiveness of some typical coffee practices on erosion reduction, four management treatments were applied at plot scale: (i) common producer management as a reference treatment, (ii) no mini-terraces renewal, (iii) weed control with only herbicide and (iv) reduced pruning of shade trees. The erosion process at plot scale was then complemented with watershed scale runoff and erosion measurements.

The objectives of this thesis are thus grouped under three main themes corresponding to one chapter each:

A- Soil erosion process description and quantification at plot scale without any treatment effect and analysis of its dynamics at three different temporal scales: annual, inter event and intra event.

B- Determination of the effects of typical alternative shade coffee management practices, on runoff, sediment concentration and soil loss. The tested practices were: no terraces renewal, weed control with herbicide-only over the year and less intensive shade tree pruning.

C- Comparison of surface runoff and erosion rates measured at coffee plot scale and at the outlet of a watershed showing about 85% of total area covered by shade coffee.

1.5 Methodological approach and hypothesis

Eight runoff plots were installed in a shade coffee system on a 65% average slope. We decided to opt for plots larger than 100 m^2 to avoid possible errors in erosion estimation when using small erosion plots that would become larger in proportion than when using large ones (Le Bissonnais et al., 1998). There was a human path track crossing transversally the coffee plantation, which obliged to split the area into two groups of runoff plots: four located on the top of the hill position and the other four plots located downhill position.

Each plot was equipped with a tipping bucket connected to a datalogger, allowing for continuous measurement of runoff. The runoff was conserved in outlet buckets with flow dividers, and sediment concentration was recorded after each big rainfall event. That means that this variable was not measured continuously. The runoff plots were installed in 2010 and were allowed to stabilize over that year since it was expected that the surface alteration -by walking around the plot and inserting the metallic walls- would produce soil detachment not associated with natural soil erosion process. Therefore, the soil erosion data from 2010 was ignored. The coffee management practices were only applied after this first, “baseline” year.

The monitoring device at the outlet of an elementary watershed was installed in 2011 and recordings began in 2012. As this region is known for violent tropical storms, responsible for repeatedly wiping away concrete recording flumes installed by ICE, the local electricity producing company, we chose to install an oversized flume, so that it would resist strong discharges. This choice obviously has consequences on the accuracy of measurements of low flows. The flume was equipped with automatic recording of both head pressure, to determine runoff, and infrared gauge, to estimate flow turbidity and therefore sediment concentration at the same temporal scale as runoff.

Our approach was based on the following assumptions:

- The plot measurements we got were representative enough of the whole plot area, which was considered large enough to encompass local soil spatial variability.
- Among the treatments applied: herbicide as only weed control would increase soil erosion, whereas less pruning pressure and terraces renewal would decrease erosion.
- Two years of data after treatment application would allow capturing some short-term trend resulting from treatment effects.
- Soil erosion processes captured at plot scale could represent most of the watershed erosion measured at the outlet (flume) since the watershed was around 85% covered by coffee crop.
- When water budget was estimated, we assumed the watershed did not leak to another watershed, or there was not subterranean water coming from a nearby watershed.

Chapter 2. Temporal dynamics of runoff and soil loss on a plot scale under a coffee plantation on steep soil (Ultisol), Costa Rica[*]

Abstract

Soil erosion is a serious threat for cultivated soils on steep slopes under tropical conditions. In Costa Rica, coffee plantations are widespread on such steep slopes in several basins used for hydroelectric generation, which are affected by soil erosion and sedimentation in dam reservoirs. For this study, surface runoff and soil loss rate were measured during three years on large experimental plots installed within a coffee field on a steep slope (60% average). The time interval for rainfall and runoff measurements was 5 minutes. A simple infiltration model presented by Diskin and Nazimov (1995) [J. Hydrol. 172, 313-330] was used to estimate runoff during a rainfall event showing the relevance of initial soil water content in order to estimate runoff base on rainfall intensity variations. Three complementary embedded time scales were analyzed: annual-monthly, event and intra-event. The rainy seasons included 581 rainfall events giving a total depth of 2206, 1778 and 2220 mm in 2011, 2012 and 2013 respectively. Total runoff was 103±55, 54±14 and 33±6.4 mm. Annual average sediment concentration was about 1.3 ± 0.3 g l^{-1} with reduced temporal variations between years or rainfall events. The total soil loss was 1686±784, 914±306 and 575±140 kg ha^{-1} for 2011, 2012 and 2013 respectively. Around 60% of rainfall and 90% of runoff and soil loss respectively came from the August-October period and more than half of it from October. Total rainfall event and soil water content explained most of surface runoff and soil loss dynamics at three time scales analyzed. Inherited soil water storage from previous year played an important role on the relationship between rainfall and runoff dynamics the following year. Soil and coffee coverage did not have a significant effect on runoff and soil loss variability due to permanently good soil coverage (even in the rainy season). This good coverage over the rainy season prevented crust development. The presence of old micro-terraces helped to reduce runoff and sediment loss. The Diskin and Nazimov model demonstrated that a combination of rainfall intensity and soil water content dynamics on an intra-event scale explained better the differences observed in runoff and soil loss on an inter-event scale. Runoff at intra event scale had high and low runoff moments depending on rainfall intensity and superficial soil layer water status and saturation of deeper layers under long rainfall events.

***Keywords**: steep slope, soil erosion, runoff, coffee, plot scale, infiltration*

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2.1. Introduction

Steep lands in tropical areas may be very susceptible to soil erosion after removal of natural vegetation due to their rough topography and erosive climate (Dadson et al., 2003; Lal, 1985; Xu et al., 2013). They are also often subject to high pressure for human subsistence and commercial agricultural purposes (Lal, 1988; Lutz et al., 1994; Sánchez and Logan, 1992; Styger et al., 2007). In Costa Rica, coffee is one of the most developed agricultural crops and coffee plantations are present in the main basins used for hydroelectricity generation, which are affected by soil erosion and sedimentation in dam reservoirs (Gómez-Delgado et al., 2011).

Producers under these extreme agricultural conditions might improve their productive systems, in terms of soil erosion mitigation, if encouraged by incentives. One such incentive in agriculture implemented in Costa Rica is called payment for environmental services (PES). PES started in 1997 and now includes agroforestry systems (Vaast et al., 2005; Pagiola, 2006) such as shade coffee plantations. However, in order to assess how much the service should be compensated, an understanding and measuring of the erosion process is called for. A study under a shade coffee plantation but on a gentler slope (<30%) was carried out by Gómez-Delgado et al. (2011). One of the contributions of their study concerned information about payment for hydrological services (PHS), which is a component of PES.

Research on the mechanisms and intensity of soil erosion on steep slopes is still limited and progress needs to be made in order to estimate the rate of erosion in steep coffee plantations under tropics conditions, and the possible mitigation measures that might compensate for it.

There are many studies of runoff and erosion processes on a plot scale but on gentle to moderate slopes (< 30%) (Hashim et al., 1995; Vacca et al., 2000; Patin et al., 2012). However, tracking runoff and soil erosion over a short time scale (over a rainfall event) and under real rainfall has yet to be reported on steep slopes under coffee plantations. Studies of coffee on steep slopes on a plot scale have been reported in Costa Rica (Vahrson and Cervantes, 1991; Gómez-Delgado, 2010; Cannavo et al., 2011), Venezuela (Ataroff and Monasterio, 1997) and Sumatra (Verbist et al., 2010). Vahrson and Cervantes (1991) measured total runoff and sediments every day from 134.5 m^2 plots under coffee (with shade trees and without shade trees) and pasture at almost 60% slope. Cannavo et al. (2011) measured total runoff and sediments after rainfall events from 1 m^2 plots under 3 and 5% slopes whereas Gómez-Delgado (2010) under similar coffee plantation (20% slope) measured same variables from two 1000 m^2 plots at daily basis and measured soil water content weekly. Ataroff and Monasterio (1997) measured cumulative runoff and sediments after 5-10 days from 12 m^2 plots under 60% slope. Verbist et al. (2010) measured runoff and sediments after rainfall events from 40 m^2 plots under 70% slope. None of the previous studies measured soil water content over rainfall events and runoff dynamics at intra-rainfall scale in real time (i.e. rainfall intensity at 5 min and runoff rate at 5 min too).

Soil erosion on steep lands does not always behave as expected; a steeper slope does not always mean more soil erosion and runoff for all types of soils and climates. Depending on the source, runoff on steep slopes has been reported to be greater, less or even without change, as compared to gentler slopes. The last case was found by Mah et al. (1992) and Cerdá and García-Fayos (1997). Less runoff as the slope increases was reported by Janeau et al. (2003), Assouline and Ben-Hur (2006), Descheemaeker et al. (2006), Ribolzi (2011) and Patin et al. (2012). Patin et al. (2012) reported a decrease in runoff with slopes increasing up to 50%, on slopes greater than 50%, runoff increased in line with the slope. Furthermore, Ribolzi et al. (2011) observed less runoff, but also less erosion (due to less crust and low detachment) on steep land (75%) compared to a 30% slope. On the other hand, greater runoff as the slope increased was observed by Fox et al. (1997), Chaplot and Le Bissonnais (2000), Khamsouk et al. (2002), Cheng et al. (2008), Yan et al. (2008), Essig et al. (2009), Shi et al. (2010) and Patin et al. (2012). Yan et al. (2008) and Shi et al. (2010) studies measured soil loss and aggregate stability up to 20% soil slope under an Ultisol. These contradictory results may be due to complex interactions between the slope gradient and other factors influencing infiltration, runoff and erosion, such as soil characteristics, vegetation cover (Anikwe et al., 2007) and soil water content (Dunne et al., 1991; Peugeot et al., 1997; Wei et al., 2007).

In terms of infiltration on steep slopes, there are some explanations for an increase or even decrease on steep slopes. Fox et al. (1997) found that the infiltration rate decreased as the slope angle increased due to a lower overland flow depth and therefore less ponding pressure head. Another explanation for this drop in infiltration is the lower raindrop density per unit of surface area, which reduces the effectiveness of rainfall intensity (estimated as the vertical rain intensity multiplied by cos α where α is the soil slope angle (Rudolph et al. 1997; Patin et al. 2012). On the other hand, factors that are related to higher infiltration rates, thus less runoff on steep lands are: (1) less formation of soil crusting (Valentin et al., 1992; Janeau et al., 2003; Patin et al., 2012;) and (2) less time in finding preferential paths to cracks or depressions with high infiltration properties whose spatial distribution is likely to be heterogeneous in the field (Gomi et al., 2008; Patin et al., 2012).

Runoff and soil loss are highly correlated with rainfall depth (Vacca et al., 2000; Gomi et al., 2008; Ghahramani and Ishikawa 2013). However, the process is not continuous during a rainfall event or during a rainy season, and depends on initial conditions, such as soil water content (Truman and Bradford, 1993; Wei et al., 2007), ground and vegetation cover (Truman et al., 2005), soil hydraulic properties, soil roughness and crusting (SCS, 1972; Le Bissonnais and Singer, 1992; Descheemaeker et al., 2006; Ribolzi et al., 2011). Also, the rainfall kinetic energy has an important role (positively affects interrill and splash soil erosion) in soil detachment process as Zhou et al. (2013) measured on Ultisol soil samples besides the aggregate stability and particles transportation distance (Wang et al., 2014). Nearing et al. (1999) analyzed a large dataset for rainfall at different site locations and observed that heavy rainfall in terms of quantity was not always related to a high runoff coefficient. However, according to Chaplot et al. (2005), in summer intense rainfall may cause a high runoff depth and peak flow on a dry soil. Thus, high rainfall accumulation can drive high runoff and soil loss depending on the temporal dynamics of other factors (Le Bissonnais et al., 1998).

There is a need to better understand the processes and determination of runoff and erosion for cultivated steep slopes in tropical areas under permanent crops such as coffee. This study was dedicated to assessing and analyzing field scale erosion under a coffee plantation on steep slopes on an Ultisol.

The objectives of this paper were: 1- to describe and quantify the surface runoff and soil erosion rate and process on a plot scale under natural rainfall events on a steep clay soil in a shade coffee plantation and 2- to determine the temporal dynamics and the influence of the main factors associated with this process on a plot scale.

2.2 Material and method

2.2.1 Experimental site

The experimental site was located (84.095326° W and 9.670427° N; 1480 m.a.s.l.) in the Pirrís watershed, 2 km west of San Isidro de León Cortés, San José, Costa Rica (Fig. 2.1A and 2.1B). The region is an extensive and very avowed coffee sector in Costa Rica amounting to around 25% of the total coffee area (93,775 ha) in the country (ICAFE, 2013). The soil classifies as an Ultisol (Soil Survey Staff, 2010), Ferrasol (FAO, 1998) or Acrisol (W.R.B., 1998) from sedimentary parental material, with a clay texture, a 170 cm average soil depth and good drainage.

There are two contrasting seasons: a dry season from December to April where scattered low rainfall occurs, and a rainy season from May to November. A weather station located in Carrizales de León Cortés (4 km away from the experimental site) registered 2444 ± 409 mm (± SD) annual average rainfall for the 1990-2006 period. The annual rainfall was below 2000 mm for only three years out of these sixteen: 1997, 2001 and 2002. This was also the case in 2012 under our study period. For the same period, the only years when annual rainfall was over 3000 mm were 1995 and 2003; this was also the case in 2010, the year preceding our study.

The previous activity at this site before the coffee plantation was pasture, around 40 years ago. The terrain for the coffee plantation was prepared by simple terracing (around a 40 cm wide flat section by shovel) and then planted with coffee. Over the last 40 years, these micro-terraces have been renewed every 8-10 years by a simple rectification of the design by shovel (last terrace renovation in 2004).

The coffee trees are interplanted with three types of shade trees: *Erythrina poeppigiana*, *Erythrina fusca* Lour and *Musa sp,* the first one being predominant.

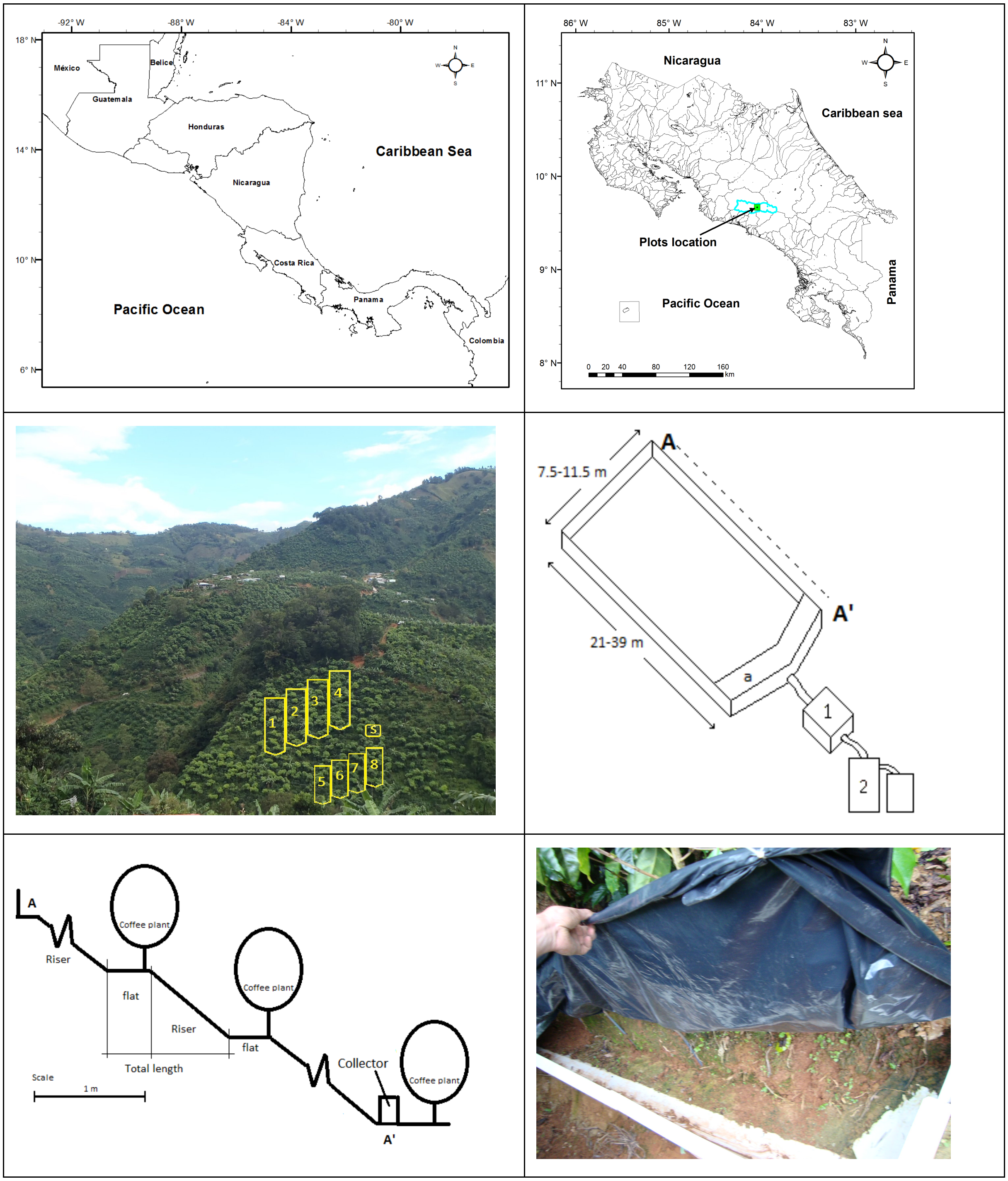

Figure 2.1. A: Central America (source: Mapquest.com). **B**: Pirrís watershed location in Costa Rica, Pacific slope (Coordinate system: WSG84). **C**: Diagram of plot distribution in the field and weather station represented as "S". **D**: Erosion plot design and dimensions where "a" is the plastic covering the collector area; 1 is the tipping bucket position and 2 represents containers for runoff storage. A to A´ dashed line is the transect sketched on section E. **E**: transversal sketch of each plot on simple terraces. **F**: Downstream position corner collector of one plot.

2.2.2 Plot characteristics

Eight erosion plots (142-340 m^2) were installed in 2010, distributed on steep land under a shade coffee plantation (Fig. 2.1 C). Four large plots (identified as 1, 2, 3 and 4) were located at the top of the hill and the remaining four smaller plots (identified as 5, 6, 7 and 8) were downhill. The plots were delimited by a metal sheet (22 cm in height) driven 5-7 cm into the soil. Due to irregular topography, the 1.2 m long metal sections had to be cut in short segments in order to follow terrain shape, especially on riser section and through coffee roots. When roots were present, a large knife (machete) was used to open and cut the line section where the metal sheet was installed. At the bottom of each plot a V type metallic trough collector was built using concrete and metal sheet. A sketch design of these plots can be found in Figure 2.1D. A flexible plastic cover was installed at the end of June 2011 to cover the collector area, diverting rainfall over this area (which would have run off to the concrete base) out of the runoff plot (Fig. 2.1D and 2.1F). The gradient of the collector was around 0.03, which helped create a sediment self-cleaning condition. Nevertheless, this was not enough during very wet periods (end of season) and the sediment in the collector area had to be removed and measured manually. A 2” flexible pipe was used to transfer runoff from collector to tipping bucket (Fig. 2.2A) and the same pipe diameter was used to calibrate the tipping buckets in the lab without problems such as pool formation under 25 l min^{-1}. Furthermore, marks on collectors’ walls were never observed, which could have indicated flood conditions on plots collectors.

Plot dimensions and other characteristics are shown in Table 2.1. The maximum possible area of the plots was calculated taking into account the expected runoff and the maximum flow that tipping buckets could measure accurately after calibration (around 25 l min^{-1}). The actual size of these plots had to be adapted to the local topography and plant distribution. Large plots could be located on the upper part of the hill (1-4, Fig 2.1 C). On the lower part, the size of the plots (5-8) was constrained by a man-made pathway crossing the plantation in a zig-zag pattern and an abrupt change in terrain slope at the bottom of the field.

Soil particle distribution was 47% ± 3.1 clay, 30% ± 2.3 silt and 23% ± 5.0 sand at a depth of 10 cm and 40% ± 5.3 clay, 30% ± 1.2 silt and 29% ± 6.2 sand at a depth of 40 cm (Meylan et al., 2013). The average soil bulk density was 1.35 ± 0.08 g cm^{-3} for the first 30 cm in depth (Nespoulous, 2011). Soil porosity was 44 and 56% at a depth of 10 and 40 cm respectively. Soil water content at field capacity and the permanent wilting point were 40 and 30% (m^3 m^{-3}) respectively at a depth of 20 cm.

The micro-terraces in the coffee field can be seen as a simple stair design with no fixed dimensions. These micro-terraces were present in all eight plots. Figure 2.1E has a sketch of a transversal terrace view where two parts (flat and riser lengths) were used to estimate the sloped section characteristic per plot. This sloped section came from the ratio of the horizontal length of the riser divided by the total length of the riser and next flat length summation (downhill direction). The sloped section value was used as a representation of which proportion of the plot was under slope conditions. The measurements were made for each coffee alley along the plots and averaged plot by plot. This average sloped section (Table 2.1) was quite similar along the plots and did not differ between upper and lower plots (t-test, p= 0.26).

The total slope of the lower plots, 5-8, was slightly higher (71%) than that of the upper plots 1-4 (61%), but this difference was not significant (t-test, *p*= 0.07). The coffee plant density averaged 7470 (S.D. 626) coffee plants ha^{-1} with no significant difference (t-test, *p*= 0.35) between upper and lower plots and the shade tree density (*Erythrina sp.*) averaged 598 (S.D. 126) trees ha^{-1} with not significant difference too (t-test, *p*= 0.50).

Table 2.1. Characteristics of runoff plots installed in a shade coffee plantation. San Isidro de León Cortés. Costa Rica

	Plot								Plots		Plots	
	1	2	3	4	5	6	7	8	1-4	SD	5-8	SD
Length (m)	31.8	39.1	39.0	33.5	27.4	24.4	23.1	21.4	**35.8**	**3.8**	**24.1**	**6.5**
Area (m^2)	320	358	339	280	171	160	142	137	**324**	**33**	**153**	**87**
Sloped area (%)*	62	65	66	73	65	64	63	62	**67**	**5**	**64**	**4**
Slope (%)*	67	57	52	69	73	66	71	74	**61**	**8**	**71**	**9**

Slope: average slope as height differences between upper and lower part of each plot divided by total horizontal length.
Sloped area: proportion of horizontal sloped section with respect to flat section and horizontal sloped length together. See Fig. 2.1E for sketch details.
*: Upper plot (1-4) vs. lower plot position (5-8) no significant difference at 5% level.
SD: Standard deviation

2.2.3 Measurements

Hydrological data were recorded from May 2011 to November 2013. Rainfall was measured using two pluviometers: an automatic pluviometer (0.1 mm capacity tip) connected to a weather station reading data every 30 min (Hobo® Onset Computer Corporation). Another automatic pluviometer (0.254 mm capacity tip) reading every 5 min was connected to a datalogger (CR-1000, Campbell Scientific Inc.). Both dataloggers were checked every week. Runoff was measured automatically per plot by a tipping bucket (1 liter capacity tip) recording every 5 min. The tipping buckets were individually calibrated in the lab in 2010, before the installation of the whole experiment (data not shown). Runoff was then collected in a 40-liter leveled container. When this first container overflowed, approximately 1:20 of the overflow was captured in a 30-liter container (Fig. 2.2). An adjustable triangle metal structure underneath each container was used for leveling both containers. However, the total runoff volume was measured by tipping buckets. The calibration of each tipping is shown in annex A. Therefore, the only information required to estimate sediment transport is the sediment concentration. This sediment concentration was measured either in the first container by sampling if this container was not overflown, or in both containers in case of overflow.

The 1/20 flow partition was not required to be very accurate, as the only assumption was that the flow that was collected had the same sediment concentration as the flow in the other 19 outlets. This should be reasonably granted. The second container never overflowed.

A sample (470 ml) for sediment concentration determination was taken after vigorous stirring in each container and each plot after each rainfall event and the containers were cleaned and emptied. The presence of coarse particles (specially in 40 L container) was limited, however some sediment samples had some coarse soil meaning the sampling methodology (previously tested in the lab) was proper. These samples were left to rest for at least 5 days until the supernatant water was clear; this clear water was then removed and the last 1-2 cm depth sample remaining was dried out in an oven for at least three days at 70°C. The bottle was then capped again until it cooled down and the remaining sediments were weighed.

Figure 2.2. **A:** Runoff tipping bucket measurement equipment and **B:** Runoff collector containers of 40 l and 30 l capacity (right).

The actual sediment concentration (in both containers) was estimated from the value measured in the sample and multiplied by 1.7 (linear adjustment with no constant, $R^2=0.95$) which was the best correction factor found after calibration using soil samples from the same plot site and the same sampling procedure. The calibration curve was very similar to the one obtained by Bagarello and Ferro (1998) using a clay soil where their coefficient was 1.8 (linear adjustment without constant).

Since there were two containers with different sediment concentration levels, the weighed (by volume) sediment concentration average was used for further estimations of soil loss. From now on we call it "gL" and it came from equation (1.1), which was applied when the first container (40 L capacity) overflowed.

$$gL = [(glc1*40) + (glc2*(TRo - 40))] / TRo \qquad (1.1)$$

Where gL is the weighed sediment concentration in g l^{-1}; glc1 is the sediment concentration in container 1 in g l^{-1}; glc2 is the sediment concentration in container 2 in g l^{-1}; TRo is the total runoff in liters per rainfall event from the plot (registered by the tipping bucket); and 40 is the capacity storage of container 1 in liters. If runoff is less than 40 l, then gL is simply equated to glc1.

The estimation of total soil loss (SL) was based on equation (1.2) where runoff (Ro) was known from the tipping bucket records and an estimation of sediment concentration taken from the sampling day was assumed for the previous rainfall event(s) after the last sampling day.

$$SL = gL * Ro *10 \qquad (1.2)$$

Where SL is soil loss in kg ha^{-1}, gL is sediment concentration in g l^{-1}, Ro is the runoff depth in mm (l m^{-2}).

Soil accumulation on the collector area was very low at the beginning of the rainy season up to the middle of October 2011 and 2013, and September 2012. The plot soil bed loads were therefore collected in October from the runoff collectors, weighed (correcting by soil water content; oven-dried at 105° for 48 h) and added to the monthly total erosion estimation.

Soil water content (SWC) was measured automatically throughout the year from permanent reflectometers (CS616, Campbell Scientific Inc.) installed parallel to the slope and recorded every 30 min on a datalogger (CR1000 Campbell model) via a multiplexer. Three points at 3 different depths (15, 30 and 60 cm) were located along the upper part of the hill slope (Plots 2, 3 and 4) and another three points were located at the bottom of the hill slope (Plots 6, 7 and 8). The soil water content measured was corrected by prior calibration in the lab of a reflectometer inserted into undisturbed soil cores from the same plot and depths. Values are reported in volumetric units (m^3 m^{-3}). The average soil water contents per depth were identified under nomenclatures W15, W30 and W60 for soil water content at 15, 30 and 60 cm depths respectively.

Between the upper and lower plots an automatic weather station (HOBO®, Onset Computer Corporation) was installed in 2010 (Fig. 2.1 C denoted as S). The data collected by this HOBO station were rainfall, temperature, sun radiation, air humidity and wind speed every 30 min. Rainfall event records were summarized on total rainfall depth by event. We considered it was relevant to separate between different types of rainfall depths that had different runoff generation and the limits were arbitrary. The three rainfall depth categories were: < 20 mm as low rainfall depths due to their low contribution to runoff production; on the opposite side, high rainfall depths were considered as above 40 mm, which usually produce high runoff; and rainfall depths in between (20 to 40 mm) were considered under medium category. Average rainfall intensity (Ri) was calculated as the total rainfall (Rf) per event divided by total rainfall time (Rt). Maximum rainfall intensities during 5 (Ri5) and 30 (Ri30) minutes were also used for data analysis.

In order to estimate soil and coffee coverage changes over the rainy season, a visual evaluation was made on each plot alley (left, center and right-hand side) approximately every two weeks and an average of all the measurements per plot was used. This visual index consisted of three levels, 1, 2 and 3, where 1 meant very low coverage, 3 very good coverage and 2 in between. Soil coverage consisted of the presence of coffee leaves, shade tree leaves (due to pruning and natural shedding), weeds and coffee twigs (coming from the removal of suckers). This soil coverage index was evaluated in two parts of the micro-terraces: the flat (Cf) and the riser (Cr) parts as is shown in Fig. 1.1E. The coffee coverage index (Cc) represented the level of coverage of the coffee inter-row by coffee leaves: if coffee branches from contiguous lines overlapped each other, the coverage was considered good (Cc=3) and if they were poorly developed so that no branch from coffee trees of adjacent rows touched each other, the coverage was poor (Cc=1). The presence of crusting/sealing phenomena was carefully checked in the field; however, no significant sealing development was observed along the monitoring period.

The experimental design was based on two blocks, corresponding to the uphill and downhill positions (one block each) where four replicates (plots) were established in each block. In 2011 all plots were managed the same way in terms of weed control, shade pruning, fertilization, coffee pruning and coffee desuckering. However, only plots 2 and 5 had the same management in 2012 and 2013, whereas the remaining plots supported different managements. Therefore data were analyzed for 2011 taking into account the eight plots as replicates. The data for 2012 and 2013 were analyzed based on the average of two plots (2 and 5) out of the eight plots, since treatment applications began in 2012. The average slope difference (<10%) between plots 2 and 5 was not expected to be relevant especially due to terraces runoff control and relatively low slope terrain differences. The standard deviation was estimated dividing the summatory of the differences (each observation minus the average) by "number of observations-1" (under sample of a population condition), which becomes one for two replicates conditions. Thus, it is still feasible to have an estimation of dispersion. Despite the relative loss in statistical significance with using only two replicates, we consider that the large size of the experimental plots (compared to many studies based on 1 m^2 plots) compensates and allows accounting for spatial variability. A test (Student t) between these two plots and the eight plots was run based on 2011 data only on a rainfall event scale in order to determine whether these two plots in 2012 and 2013 could be used as a continuation of the 2011 data trend. There was no significant difference (5% level) between these two plots and the eight together in 2011, so the data for the three years in a row were used, although this increased the standard deviation for 2012 and 2013 data.

2.2.3 Data analysis

The data analysis set out to identify the main factors explaining the runoff generation and erosion processes. In order to do that, three complementary embedded time scales were studied: annual-monthly, inter-event and intra-event. A correlation analysis was only feasible at inter-event scale where variables were available at that scale. Annual or even monthly correlation analysis implied gross averages with very high variability due to time effect. On the other hand, intra-event correlation analysis required sediment concentration data and soil water content changes at 5 min laps, which were not possible. Only two variables available at 5 min scale were runoff and rainfall intensity, but the different runoff concentration times per plots overestimated runoff sometimes and lag time (for runoff covering whole plot length) was not exactly 5 min lap.

A rainfall event was considered as the moment when rainfall started until no more runoff was registered from the plot (tipping signal) even after rainfall had finished. If no runoff was registered, the event finished at the end of the rainfall. Furthermore, in order to separate contiguous rainfall events, a period of 90 min without rainfall was determined as a threshold, after which any rainfall pertained to a new rainfall event. In terms of rainfall depth and minimum time lap, if rainfall was equal to 0.25 mm in 5 min then it was ignored if no more rainfall was registered over the next 90 min. Otherwise it was considered as part of the rainfall event.

2.2.3.1 Annual-monthly scale

The analysis on the annual and monthly scale set out to explain the annual distribution of both runoff and erosion, and to study the correlation between them. Analyses were conducted for the three consecutive years 2011, 2012, 2013. On both the annual and monthly time scales, the variables studied were:

- Total rainfall (Rf: mm) cumulated per month summing up all rainfall events registered.
- Average rainfall intensity (Ri: mm h^{-1}) defined as total rainfall depth divided by total rainfall duration from the beginning of the rainfall event to the end.
- Total runoff (Ro: mm) measured from runoff collected on plots for each rainfall event and normalized dividing by the total plot area.
- Mean sediment concentrations (gl: g l^{-1}) measured by taking a sample from total or partial runoff collected (if runoff exceeds 40 liters) in containers after each rainfall event.
- Total soil loss (SL) estimated by the product of total runoff (Ro) and sediment concentration (gl) and adjusted to kg ha^{-1}.

2.2.3.2 Inter-event scale

This second temporal scale of analysis was intended to quantify the contribution of each rainfall event and to explain the runoff and erosion processes on the event scale considered as a whole. These data were analyzed as one dataset using 2011-2013 together and checked for normality distribution (Shapiro Wilk test). If normality could not be reached even by transformation then non-parametric correlation and graphical analysis were carried out. Three groups of events were defined according to the total rainfall depth (Table 2.3): lower than 20 mm (denoted as group L), between 20 and 40 mm (group M), and higher than 40 mm (group H). Hence, each month could be characterized by the number of events “n”. Then, on the event scale a cross-correlation analysis was conducted using the following variables:

- Total runoff (Ro) as the total liters of runoff per square meter, thus mm.
- Sediment concentration (gl) reported as grams per liter.
- Soil loss (SL) reported as kg per hectare and estimated as the multiplication of average sediment concentrations by total runoff.
- Rainfall characteristics: Rf as the total rainfall depth in mm; Rt as the total rainfall duration in minutes from the beginning of the event until rainfall

stopped. However, in the event that there was still some runoff recorded after rainfall stopped, the rainfall event duration was until the last runoff recorded; Ri5 as the maximum rainfall intensity in 5 min and Ri30 as the maximum rainfall intensity in 30 min (mm h^{-1}).

- Initial soil water content conditions estimated as volumetric soil water content measured by reflectometers at depths of 15, 30 and 60 cm (W15, W30 and W60 respectively).
- Visual soil and coffee coverage where Cf is coverage of the flat terrace section, Cr is coverage of the riser terrace section and Cc is coverage of coffee plants evaluated along coffee alleys (qualitative scoring).

Runoff, sediment concentration and soil loss were the dependent variables and the remaining ones were the independent variables.

Since soil water content at a depth of 15 cm was more related to soil surface moisture conditions, rainfall events and their respective runoff records were grouped based on three initial soil water content ranges at a depth of 15 cm (W15). Soil water content was considered to be low when values were below 35%. Soil water contents between 35 and 40% were considered to be medium values and soil water contents above 40% were considered to be very high (close to saturation state).

2.2.3.3 Intra-event scale

While the previous time scale considered global rainfall intensity on an event scale, some factors explaining runoff and erosion linked to short time steps were ignored, such as the temporal distribution of rainfall intensities, the maximum instantaneous rainfall intensity, the evolution of surface soil moisture during a rainy event, especially for multiple rainfall events where soil moisture can vary up and down during the event. The methodology proposed focuses on some critical rainfall-runoff events causing the greatest runoff coefficients and erosion quantities. These were analyzed in more detail (at 5 min intervals), which were called intra-rainfall events in terms of rainfall, runoff and infiltration only (sediment concentration was measured only once per event). Infiltration was considered as the difference between total rainfall (mm) and total runoff (mm). In order to model the total amount of runoff taking into account the temporal distribution of rainfall at 5-min time steps, runoff-infiltration models on a the plot scale are generally used (see for example a comparison of different models in Chahinian et al. (2005)). Here, the Diskin and Nazimov infiltration-runoff model (Diskin and Nazimov, 1995) was chosen because the model is parsimonious and well adapted for hydrologic rainfall-runoff applications (e.g. Moussa and Chahinian, 2009).

Lumped conceptual rainfall-runoff models are largely used in hydrology at both the catchment (e.g. Charlier et al., 2008; Duan et al., 1992; Gomez-Delgado et al., 2011; Moussa and Chahinian, 2009; Singh, 1995) and the plot scale (e.g. Chahinian et al., 2005, 2006; Charlier et al., 2009). They have a conceptual structure based on the interaction between storage elements representing the different processes, with mathematical functions to describe the fluxes between the stores.

The modelling approach followed herein will be lumped and the plot will be considered as a single entity. A one-reservoir model was used on the basis of the Diskin and Nazimov (1995) production function (Fig. A1). Evaporation is not represented since the purpose of the model is to simulate individual flood events during which evapotranspiration is negligible. In the literature, the Diskin and Nazimov model was modified and adapted for various hydrological applications, such as spatially distributed hydrological modelling (Moussa et al., 2007) and lumped modelling of medium size (~100 to 1000 km²; Moussa and Chahinian, 2009) and small catchments (~1km²; Charlier et al., 2008; Gomez-Delgado et al., 2011). Herein we extend the application of the Diskin and Nazimov model at the plot scale (~100 m²) on the basis of lumped conceptual approaches proposed by Chahinian et al. (2005, 2006).

At each time t, a regulating element f [ms^{-1}] separates rainfall R [m] into surface runoff y [m], and infiltration q [m]. The soil-reservoir element has one input, the infiltration q [m], and one output g [$m\ s^{-1}$] (eq. 1.6), which represents the percolation from the upper soil layer to deeper layers. The state variable of the regulating element, denoted f, (eq. 1.3) is determined by the magnitude of the reservoir state variable S according to the Diskin and Nazimov (1995) relationship (Fig. A2)

$$f = f_0 + (f_c - f_0)\frac{S}{Sm} \tag{1.3}$$

where f_0 [ms^{-1}] is the maximum infiltration capacity (corresponding to S = 0), f_c [ms^{-1}] the minimum infiltration capacity (corresponding to $S = S_m$), and S_m [m] the maximum storage in the soil-reservoir layer. The value of f_c characterises the soil's infiltration capacity at saturation, and the term (S/S_m) characterises the relative soil moisture. The two outputs y and q of the regulating element depend on the value of the state variable f and on the value of the input R, at the same instant according to the following equations:

$$\text{If } R < f \quad \text{then} \quad q = R \quad \text{and} \quad y = 0 \tag{1.4}$$

$$\text{If } R > f \quad \text{then} \quad q = f \quad \text{and} \quad y = R - f \tag{1.5}$$

The outputs of the soil-reservoir g are calculated as function of S such as (Fig. B2)

$$g = f_c\frac{S}{S_m} \tag{1.6}$$

It should be noted that if the storage S approaches the threshold value S_m, both the infiltration capacity f and the sum g tend to the same value f_c (Fig. B2). Then, a moving average function with three or more time steps is applied (Fig. 2.6) to smooth y(t) in order to simulate the dispersion process when routing flood events.
The objective herein is not to simulate the output hydrograph y(t) or runoff at each time step t, but the total runoff for each flood event $\sum_{o<t<T} y(t).A$ (t being the event duration and A [m²] the plot area).

Annex B presents the model structure, the input variables, the model parameters and the calibration strategy. The following model parameters were estimated by optimization of two out of three original parameters: *fo* as maximum infiltration capacity when superficial soil layer water content storage is very low (close to the wilting point); *fc* is the minimum infiltration capacity when superficial soil water content is at saturation point. The initial condition in terms of soil water content of the superficial soil layer determined the initial soil infiltration capacity at the beginning of the rainfall event. Also, maximum and minimum soil water contents (S_m and S_{min} respectively) were determined in order to estimate the soil water storage capacity (S), which was estimated from field soil samples.

This model was applied in this study to rainfall events where runoff was higher than a depth of one mm. Then, the distribution of rainfall events based on total runoff depth categories were compared with the same category distribution of estimated runoff depths for each rainfall event to see if they were alike in distribution line shape.

2.3. RESULTS

2.3.1 Annual and monthly data analysis

The monthly trends as monthly cumulative values are presented for rainfall, total runoff and total soil loss. The monthly average: soil water content and sediment concentration are also presented in this section as a general trend.

Measurements started in May 2011 at the beginning of the rainy season. However, the sediment concentration data started in July 2011 since collectors did not yet have the plastic covers in May and June, which affected rainfall interception and soil detachment under the transition zone between concrete collectors section and plot soil surface. These missing erosion data do not significantly impact the total erosion calculation for 2011 since runoff amount was very low for the May–June period.

2.3.1.1 Rainfall trends

Total rainfalls over the rainy seasons (May-Nov., Table 2.2) were similar in 2011 and 2013, whereas 2012 was the lowest not only over these three years period but also since 2002

(1783 mm May-Nov. period). This 2012 rainy season was considered a dry year because it was below the last ten-year rainy season period average (2307 ± 393 mm) minus one standard deviation.

Rainy season rainfall trends were similar over the three years (Table 2.2 and Fig. 2.3) increasing from the onset of the rainy season. Major rainfall accumulation occurred from August to October, which amounted to around 60% of the total rainfall (May-Nov). October 2011 and 2013 and August 2012 had the highest monthly rainfall accumulation in the year.

Maximum average rainfall intensities (2.2) did not present the same pattern over these three years. Maximum values for average rainfall intensity in 2011, 2012 and 2013 were in September-October, August and June respectively. In November there was always constant low maximum average rainfall intensity as the dry season began. High values for this variable in August 2012 corresponded with the highest rainfall accumulation month that year (Fig. 2.3); however, this match was not found for the other two years.

2.3.1.2 Soil water content trends

Soil water content (15, 30 and 60 cm depths) had a similar trend for 2011 and 2013 with a peak in October, whereas in 2012 that peak was not present in October and decayed instead. Fig. 2.3 uses W30 as a proxy for average of other two depths (15 and 60 cm) where W30 was around 1% higher but consistent compared with average from W15 and W60.

Low values started at the onset of the rainy season then increased to a maximum in September for 2012 and October for 2011 and 2013, then fell in November in all cases. In 2012 soil water content did not increase as much as in the previous and following year. Maximum monthly average W30 reached around 35 and 40% in October 2013 and 2011 respectively. However, the monthly W30 average never reached 35% in 2012. In absolute values, 2011 could be considered as a normal rainy year, whereas 2012 and 2013 were drier, especially 2012. Soil water storage at the beginning of 2013, inherited from the previous dry year, was much lower than in 2012 as a consequence of a relatively rainy year in 2011. In 2011 initial soil water content was much higher than 2012 and 2013 and that could have an important effect of annual runoff generation. 2010 was a very rainy year reaching 3564 mm (not in Table 2.2), which was around 1000 mm above the last ten-year average.

2.3.1.3 Runoff trends

Total annual runoff depths were 103, 54 and 33 mm for 2011, 2012 and 2013 respectively. Most of the runoff over the year was registered in October: between 55% (2012) and 70% (2011) of the total annual runoff. However, this month had between 18 and 33% of the total rainfall during the rainy season (2012 and 2011 respectively).

On the other hand, the beginning of the rainy season (May-July) was a period of low runoff (< 4.5% of annual runoff) and accounted for no more than 8% of annual rainfall. Furthermore, in 2013, the increment in runoff as rainfall increased (at the onset of the rainy season) was late compared to the previous two years (Fig. 2.3) where October 2011 had the highest runoff accumulation per month over the three years.

2.3.1.4 Erosion trends

Sediment concentration was relatively low and constant over the three years (Table 2.2). Average annual values did not change much, ranging between 1.15 ± 0.41 and 1.49 ± 0.42 g l^{-1} (average ± 1 S.D.) for 2013 and 2011 respectively. Statistical comparisons (t test) between the three years confirmed the annual means were statistically the same (5% level) and also when comparing the same month each year.

Annual soil loss was lower in 2012 and 2013 than in 2011. Total soil loss was 1.69 ± 0.78 t ha^{-1} in 2011, dropping to 0.91 ± 0.31 t ha^{-1} in 2012 and continuing to fall in 2013 with 0.57 ± 0.14 t ha^{-1}. Despite this decreasing soil loss rate, October still had the major proportion of the total soil loss each year. October had 75% of the annual total soil loss in 2011 and 2013 dropping to 47% in 2012. This high October contribution can be seen in Fig. 2.3.

Table 2.2. Summary of rainfall, runoff and sediment variables for 2011-2013 on a plot scale. San Isidro de León Cortés. Costa Rica

Variable	**Year**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Annual**$^{+}$
Total rainfall (mm)	*2011*	197	303	287	321	271	728	99	2206
	2012	263	221	208	410	289	316	71	1778
	2013	281	343	162	289	495	508	142	2220
Maximum average rainfall intensity (mm h^{-1})*	*2011*	16	9	12	12	20	20	8	20
	2012	13	14	11	33	6	17	8	33
	2013	7	21	8	17	13	13	10	21
Total runoff depth (mm)	*2011*	1.40	3.21	3.79	7.11	10.6	71.6	4.83	**103**
		(0.48)	*(1.27)*	*(2.10)*	*(4.43)*	*(4.70)*	*(41.2)*	*(2.47)*	*(55)*
	2012	0.43	0.61	1.35	12.2	7.95	29.7	1.61	**54**
		(0.12)	(0.27)	(0.49)	(2.41)	(1.64)	(10.4)	(0.53)	(14)
	2013	0.25	0.74	0.61	1.62	7.78	21.6	0.78	**33**
		(0.24)	(0.31)	(0.20)	(0.42)	(2.33)	(6.10)	*(0.14)*	*(6.4)*
Sediment concentration (g l^{-1})	*2011*	-	-	1.57	0.94	1.32	1.51	1.05	**1.28**$^{\#}$
		-	-	*(0.55)*	*(0.33)*	*(0.41)*	*(0.59)*	*(0.23)*	*(0.28)*
	2012	1.03	1.73	1.89	1.62	1.11	1.23	1.37	**1.43**
		(0.62)	*(0.70)*	*(0.45)*	*(0.49)*	*(0.47)*	*(0.72)*	*(0.69)*	(0.42)
	2013	0.96	1.11	1.09	1.11	1.27	1.82	0.62	**1.14**
		(0.59)	*(0.63)*	*(0.45)*	*(0.46)*	*(0.30)*	*(0.41)*	*(0.34)*	*(0.36)*
Total soil loss (kg ha^{-1})	*2011*	-	-	82.9	74.3	159	1152^{bl}	100	**1686**$^{\#}$
		-	-	*(42.8)*	*(53.8)*	*(65.1)*	*(602)*	*(60.0)*	*(784)*
	2012	5.33	11.1	15.4	223	157^{bl}	486	6.68	**914**
		(2.40)	*(4.89)*	*(9.59)*	*(59.2)*	*(33.0)*	*(226)*	*(11.4)*	(306)
	2013	*2.48*	*11.0*	*7.44*	*15.7*	*114*	*420*^{bl}	*4.56*	**575**
		(2.04)	*(11.0)*	*(2.88)*	*(6.76)*	*(41.0)*	*(120)*	*(2.07)*	*(140)*

Standard deviation in brackets

$^{+}$: Total rainfall corresponds to the May-Nov. period.

^{bl}: Soil loss in these months had extra soil loss collected from the plot collector trough, called bed load.

*: Maximum average rainfall intensities were calculated from the total rainfall event divided by the total rainfall time event.

$^{\#}$: These annual values (May and June) are missing data due to disturbed sediment samples.

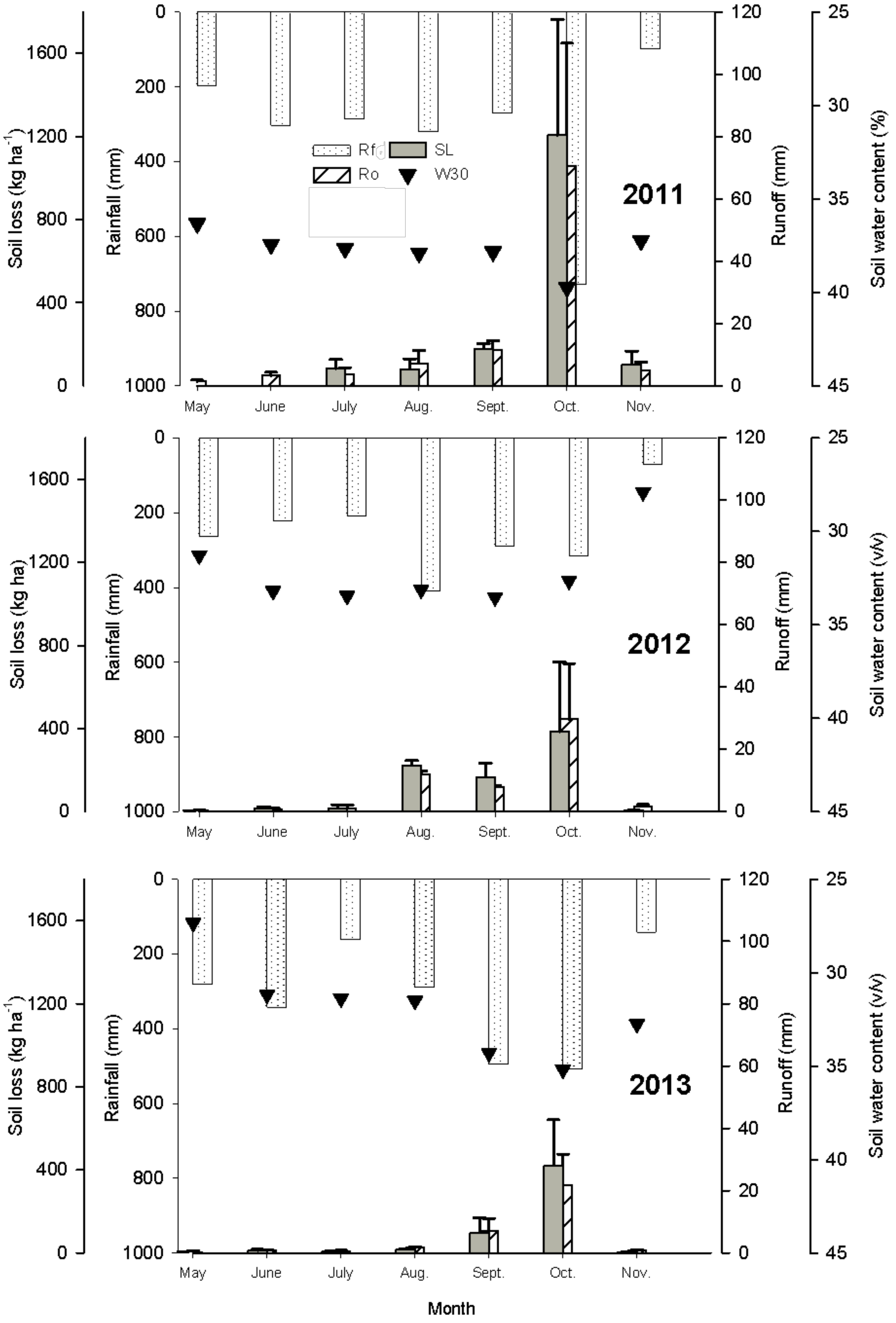

Figure 2.3. Monthly runoff depth (RO), soil loss (SL), soil water content at a depth of 30 cm (W30) and total rainfall (Rf). Vertical bars are one standard deviation.

On an annual scale, most of the rainfall and runoff and soil loss occurred at the end of the rainy season, where October was the month when more than half of the annual runoff and soil loss was recorded. Sediment concentration did not seem to be an explanation for this since it was quite stable. Therefore, an analysis on the scale of rainfall events was performed in order to more effectively explain the observed trends.

2.3.2 Event data analysis

Fig. 2.4 shows in more detail the information summarized in Fig. 2.3. Instead of monthly averages, the values for each rainfall event were used. The same variables as those used in Fig. 2.3 are presented as cumulative values in order to facilitate the comparison between the three years.

2.3.2.1 Rainfall event characteristics

The rainy seasons of 2011, 2012 and 2013 (May-Nov.) registered 213, 204 and 179 rainfall events respectively. In 2011, 23% of the rainfall events occurred in October followed by 16% in June. In 2012, 19% and 18% of rainfall events occurred in October and May respectively. In 2013, 18% of the total rainfall events were in September and 15% each in June, August, and October. Rainfall distribution was sparser in 2013.

Most of the rainfall events (83, 87 and 79% in 2011, 2012 and 2013 respectively) were in the group below the 20 mm rainfall depth (Table 2.3). Their contribution to annual rainfall was 41, 52 and 41% in 2011, 2012 and 2013 respectively. This rainfall group contributed to 13, 24 and 17% of annual runoff and to 13, 25 and 17% of annual soil loss for 2011, 2012 and 2013 respectively.

The medium range rainfall depth group (20-40 mm) corresponded to 13, 10 and 16% of the total rainfall events accounting for 31, 32 and 35% of total rainfall depth for 2011, 2012 and 2013 respectively. In terms of runoff, they produced 29, 64 and 33% and in terms of soil loss, 25, 62 and 30% for 2011, 2012 and 2013 respectively.

Rainfall events > 40 mm corresponded to only 4, 3 and 5% of total rainfall events accounting for 28, 16 and 24% of total rainfall for 2011, 2012 and 2013 respectively. However, in terms of runoff they corresponded to 58, 12 and 50% and in terms of soil loss, 62, 13 and 53% for 2011, 2012 and 2013 respectively. In 2012 there were few rainfall events greater than a depth of 40 mm (6 events from June to August) whereas there were 9 in 2011 and 2013 and, of these 9 events, almost half of them occurred in September and October.

The rainfall slope cumulative curves had similar increments (just slightly steeper in 2013) up to the end of August (Fig. 2.4) each year, then a slight pause, followed just after by a steeper curve beginning in October, which was even steeper in 2011. Similar but shorter rainfall concentration was observed at the end of October 2012. In 2013, the rainfall accumulation trend did not show a similar rainfall concentration in a short period (October), where rainfall was more distributed throughout the month.

2.3.2.2 Soil water content event characteristics

The soil water content plotted in Fig. 2.4 came from the measurement of reflectometers at a depth of 30 cm (W30) and corresponds to the initial condition at the time of the rainfall event. This W30 is not the same as the average presented in Fig 2.3, which is a monthly W30 average instead, which does not represent initial soil condition in terms of soil water content. Consequently, Fig. 2.4 gives a more dynamic soil water content just before a rainfall event started and more related to runoff generation than average soil water content over whole rainfall event. The scatter of these points from May to September is similar in the sense that the W30 varied a lot from one rainfall event to the next. However, most of the runoff occurred when W30 was high (moving towards 40%). This was more evident in 2011 where a group of high W30 points remained closer to 40% and did not drop much, meaning very frequent rainfall over that period. This was also visible at the end of October 2012 and a few times in October 2013.

November still had some rainfall events, but less often, thus the soil had time to dry out between events (Fig. 2.4).

2.3.2.3 Runoff event characteristics

Runoff in 2011, 2012 and 2013 (May-Nov.) was produced by 78, 56 and 63% of total rainfall events respectively (data not shown). Therefore between 22 and 44% of total rainfall events did not produce runoff and all of them were below 11.7 mm (only one event with this depth, the remaining ones were below 8.6 mm) rainfall event depth.

The three rainy season patterns for 2011, 2012 and 2013 had different runoff accumulation when looking at the event scale. Runoff followed a smooth increasing pattern in 2011 up to October, which had a considerable increment (steeper slope, Fig. 2.4). In 2012, there was a faster increment in cumulated runoff at the end of August and another even larger one in the middle of October. Meanwhile, 2013 had two small increments in cumulated runoff at the beginning and end of October only.

Besides the difference in the runoff accumulation rate between the three years, in 2011 there was a much higher runoff accumulation rate than in the following two years (Table

2.2). In fact, it was a little more than two- and three-folds compared with 2012 and 2013 respectively.

2.3.2.4 Erosion event characteristics

Soil loss variability was highly related to runoff, since sediment concentration did not change much over the year. Therefore, soil loss followed the same trend as runoff (Fig. 2.4), where October was the month each year that had the highest increment in runoff and soil loss. In 2011 and 2013 sediment concentration tended to increase to a maximum (not far from the annual average) in October (1.51 and 1.82 g l^{-1} respectively). A similar peak was observed in sediment concentration in July 2012 (1.89 g l^{-1}).

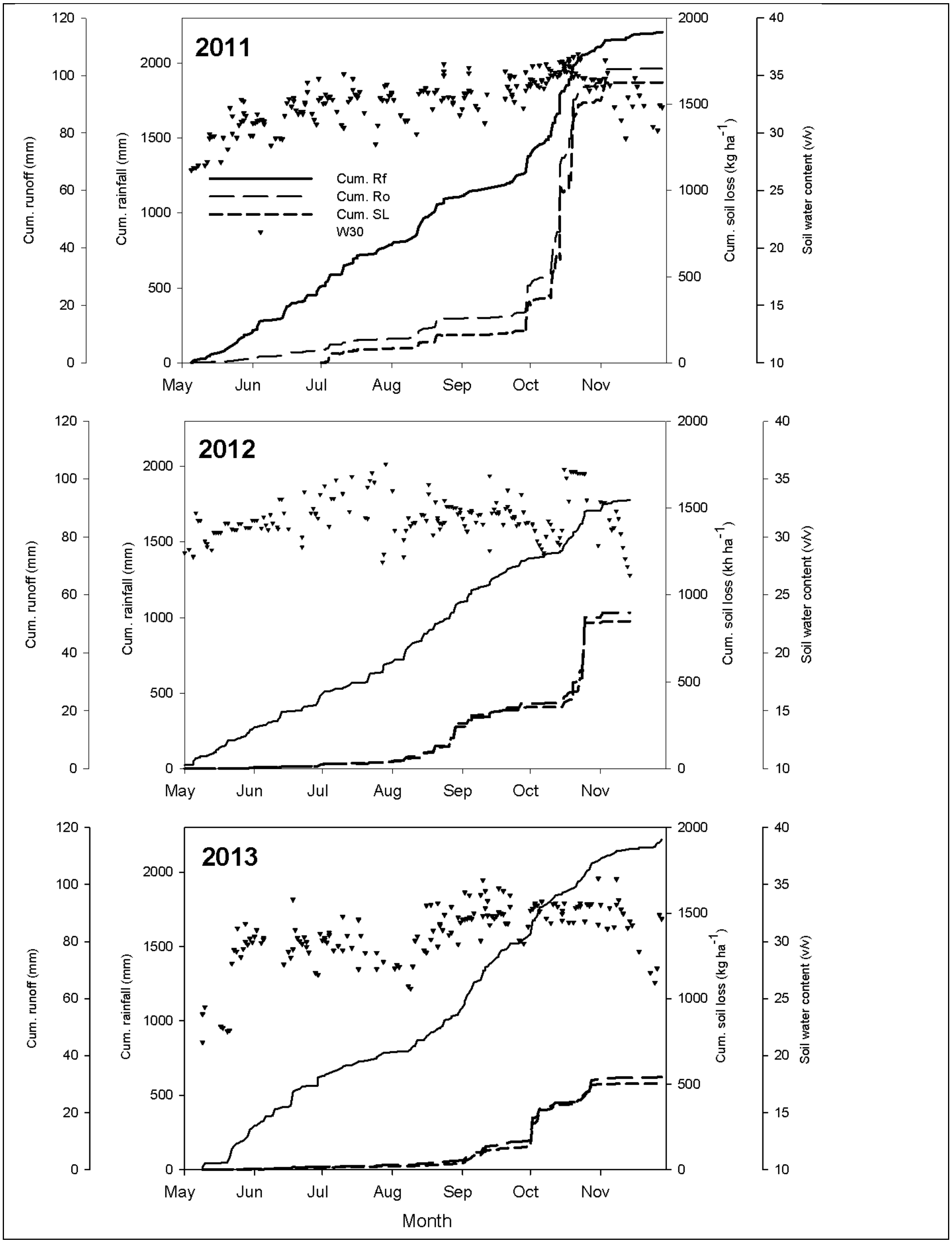

Figure 2.4. Cumulative rainfall (mm), runoff (mm) and sediment loss (kg ha^{-1}), average soil water content at a depth of 30 cm per rain event. 2011-2013.

Table 2.3. Rainfall categories based on three total depths (**L**: < 20 mm; **M**: 20-40 mm and **H**: > 40 mm) per event and number of events (n). Rainfall periods (May to November) from 2011 to 2013.

		May			June			July			Aug.			Sept.			Oct.			Nov.			May-Nov.		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
2011	**mm**	145	41	0	128	132	42	144	51	93	102	115	104	104	67	100	194	267	267	73	26	0	**890**	**699**	**606**
	%mm	*7*	*2*	*0*	*6*	*6*	*2*	*7*	*2*	*4*	*5*	*5*	*5*	*5*	*3*	*5*	*9*	*12*	*12*	*3*	*1*	*0*	***41***	***31***	***28***
	n	24	2	0	28	5	1	25	2	2	20	4	2	23	3	1	37	10	3	19	1	0	**176**	**27**	**9**
	%n	*11*	*1*	-	*13*	*2*	*0*	*12*	*1*	*1*	*9*	*2*	*1*	*11*	*1*	*0*	*17*	*5*	*1*	*9*	*0*	-	***83***	***13***	***4***
2012	**mm**	157	106	0	116	23	82	84	28	95	199	106	105	182	106	0	144	171	0	41	30	0	**923**	**570**	**282**
	%mm	*9*	*6*	*0*	*7*	*1*	*5*	*5*	*2*	*5*	*11*	*6*	*6*	*10*	*6*	*0*	*8*	*10*	*0*	*2*	*2*	*0*	***52***	***32***	***16***
	n	32	4	0	21	1	2	16	1	2	29	3	2	31	4	0	32	6	0	17	1	0	**178**	**20**	**6**
	%n	*16*	*2*	-	*10*	*0*	*1*	*8*	*0*	*1*	*14*	*1*	*1*	*15*	*2*	-	*16*	*3*	-	*8*	*0*	-	***87***	***10***	***3***
2013	**mm**	120	60	102	99	55	190	112	50	0	120	169	0	196	258	41	192	127	189	77	65	0	**916**	**784**	**522**
	%mm	*5*	*3*	*5*	*4*	*2*	*9*	*5*	*2*	*0*	*5*	*8*	*0*	*9*	*12*	*2*	*9*	*6*	*9*	*3*	*3*	*0*	***41***	***35***	***24***
	n	14	2	2	23	2	3	22	2	0	23	6	0	22	9	1	21	4	3	17	3	0	**142**	**28**	**9**
	%n	*8*	*1*	*1*	*13*	*1*	*2*	*12*	*1*	-	*13*	*3*	-	*12*	*5*	*1*	*12*	*2*	*2*	*9*	*2*	-	***79***	***16***	***5***

%mm: it refers to total rainfall in mm per depth category with respect to total rainy season (May-Nov.) cumulative depth.
%n: it refers to total rainfall events with respect to total rainy season (May-Nov.) rainfall events.
n: number of rainfall events.

2.3.2.5 Relationships between runoff, erosion and explanatory factors

The database for the rainfall event scale did not pass the normal distribution test. Typical transformation equations were applied in order to normalize the data, and none of them transformed the data enough to pass the normality test. Thus, a Spearman correlation analysis was carried out using data from the three years together (Table 2.4), where dependent variables (Ro, gl and SL) and independent variables (Rf, Ri5, Ri30, Rt, W15, W30, W60, Cf, Cr and Cc) were included.

Runoff was highly correlated with rainfall characteristics (Rf, Ri5, Ri30 and Rt, Table 2.4) where Rf had the strongest correlation (R=0.88 and p<0.001). Soil water contents at depths of 15, 30 and 60 cm were significantly correlated with runoff (R=0.20-0.26 and p<0.001). The soil coverage indexes for the flat part of the terraces were significantly but positively correlated with runoff (R=0.18, p<0.001). This positive correlation may have been related to a higher soil water content due to greater soil coverage or the fact that this index was always close to three (maximum index possible) with small changes over the year, but increasing towards the end of the rainy season (September-October), where rainfall events were more frequent and heavier. The coffee coverage index was negatively and significantly (R=0.10, p<0.05) correlated with runoff, although this index was quite constant over the year as well. The riser coverage index was the one that fluctuated most over the year, where the peak was measured at the beginning of September (2.40 ± 0.43) but was not significantly correlated with runoff.

Sediment concentration (gL) was very loosely (R=0.07 to 0.13) but significantly ($p<0.01$) correlated to rainfall characteristics, except for rainfall intensity at 5 min (Ri5). Soil water content at depths of 30 and 60 cm had low but significant correlation values ($p<0.01$) with sediment concentration. The soil coverage on the riser was negatively and significantly correlated with sediment concentration, as well as coffee coverage ($p< 0.001$ and 0.05 respectively). Soil coverage on the riser was the independent variable that was best correlated to sediment concentration.

Soil loss (SL) had a high correlation index with rainfall characteristics especially with rainfall depth (R=0.86 and $p<0.001$). Soil water contents at 15, 30 and 60 cm were loosely but significantly correlated to soil loss ($p<0.001$).

Rainfall depth presented the higher correlation (Spearman coefficient) with runoff and soil loss, whereas soil water content was low correlated with same dependent variables, but significant correlated.

The explanatory variables, rainfall depth, intensity and duration, were highly correlated, $p<0.001$). The situation was the same for the soil water content at three depths and soil coverage of the flat section of the terraces (Cf). In fact, when visual coverage evaluations were carried out, an obvious pattern was observed; the greater the coffee density was, the less the soil coverage was in the flat and riser parts of the terraces (the latter was not reflected in the correlation values, Table 2.4).

Fig. 2.5 shows a scatter approach for rainfall depth against total runoff per event. The soil water content was highly correlated with runoff, so the data for Fig. 2.5 were split into three groups based on W15 measurements. The groups were W15 < 30%, 30-35% and >35%. The new adjusting potential curves, also observed as good fit curves by Ghahramani and Ishikawa (2013), improved in terms of the coefficient of determination (R^2: 0.72 when no soil water content was used as a grouping criteria). Basically, no runoff or very little runoff was measured when the initial soil water content was below 30% (Fig. 2.5 the small graph embedded at the bottom right shows the scatter points in detail). Then, runoff increased (compared to initial soil water content <30%) as the initial soil water content was between 30-35%, and got even higher as initial soil water content was above 35%.

Fig. 2.5 was used to determine the rainfall depth threshold for the start of runoff on an event scale. The rainfall events where runoff was very low (< 0.005 mm) were selected and split by the soil water content at a depth of 15 cm (W15). Based on this approach, the threshold when W15 < 30 % was 7.5 ± 4.5 mm (average ± S.D.), when 30% < W15 < 35%, the threshold was 2.7 ± 1.9 mm and when W15 > 35% threshold was 1.9 ± 1.2 mm. The number of observations for each group was 41, 40 and 17 respectively. Thus, the higher the initial soil water content was the more runoff occurred even with low rainfall depth events.

About half of the annual runoff and soil loss came from rainfall events at a depth >40 mm, which corresponded to one fifth of the total rainy season rainfall. Those extreme events played an important role in runoff and soil loss. Nevertheless, sediment concentration was loosely correlated with rainfall characteristics. Soil water content was the other variable (besides rainfall) that showed a substantial contribution to the variability in runoff and sediment loss. The cumulative runoff, soil loss and rainfall per event analysis showed good correlations. However, particular dynamics were expected over each event where runoff and soil water content changed as the rainfall intensity fluctuated. Therefore, a further more detailed intra-rainfall data analysis was performed to gain a clearer understanding of the runoff process and the effects of the explanatory variables considered.

Table 2.4. Spearman rank order correlation coefficients between dependent variables (in bold) and explanatory variables measured in the field. Data from plots averaged from 2011-2013.

n:581	**Ro**	**gl**	**SL**	Rf	Rt	Ri5	Ri30	W15	W30	W60	Cf	Cr	Cc
Ro	1												
gL	0.21*	1											
SL	0.99*	0.31*	1										
Rf	0.88*	0.11+	0.86*	1									
Ri5	0.64*	0.07	0.62*	0.75*	1								
Ri30	0.79*	0.13#	0.78*	0.86*	0.45*	1							
Rt	0.84*	0.12#	0.82*	0.93*	0.51*	0.95*	1						
W15	0.26*	0.07	0.26*	0.06	0.14#	-0.00	0.01	1					
W30	0.20*	0.16*	0.21*	0.03	0.11+	-0.00	0.00	0.87*	1				
W60	0.21*	0.13#	0.22*	0.02	0.12#	-0.02	-0.03	0.90*	0.85*	1			
Cf	0.18*	0.02	0.17*	0.06	0.11+	0.03	0.03	0.52*	0.36*	0.50*	1		
Cr	0.01	-0.30*	-0.04	0.04	-0.01	0.02	0.06	0.08	0.01	0.08	0.31*	1	
Cc	-0.10+	-0.11+	-0.12#	-0.04	0.01	-0.04	-0.06	0.08	0.10+	0.08	-0.02	-0.16*	1

Ro: runoff depth (mm), **gL**: sediment concentration ($g*l^{-1}$); **SL**: soil loss ($kg*ha^{-1}$), Rf: rainfall depth (mm); **Ri**5: maximum rainfall intensity in 5 min; **Ri30**: maximum rainfall intensity in 30 min; **Rt**: rainfall duration (min); **W15**: soil water content at a depth of 15 cm ($m^3\ m^{-3}$); **W30**: soil water content at a depth of 30 cm ($m^3\ m^{-3}$); **W60**: soil water content at a depth of 60 cm ($m^3\ m^{-3}$); **Cf**: visual coverage index for the flat section of the plot (1-3); **Cr**: visual soil coverage index for the riser of the plot and **Cc:** visual coffee coverage index.

n: number of observations

+, # and *****: $p < 0.05$, <0.01 and <0.001 respectively

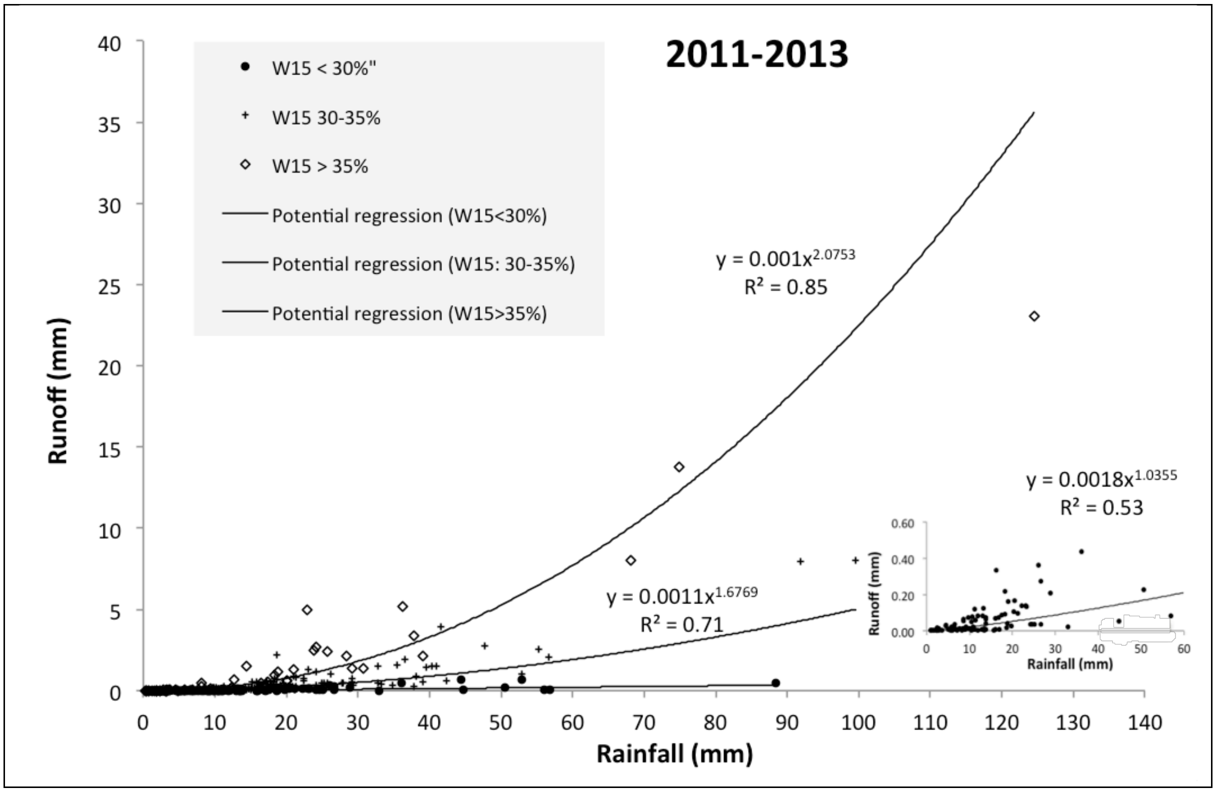

Figure 2.5. Scatter plot and best fitting regression lines between runoff explained by rainfall on three different soil water contents as the initial condition. The embedded graph shows extreme points when soil moisture < 30%.

2.3.3 Intra-rainfall event analysis

The runoff dynamics for the main events were analyzed using the Diskin & Nazimov (1995) model, which can be used to estimate excess rainfall equivalent to runoff on the basis of rainfall characteristics and soil water content. A total of 27 out of 40 rainfall events with runoff records at a depth of over 1 mm were selected for this analysis. The 40 and 27 events amounted to 78 and 55% of total runoff over the three rainy seasons. However, a good soil water content measurement was only available for the 27 events selected. Since the soil water content at a depth of 15 cm (W15) represented the water storage status of the superficial soil layer, it was used as the initial condition.

The infiltration model was optimized by adjusting the maximum and minimum infiltration capacity parameters, *fo* and *fc,* respectively. The maximum soil water content (*Sm*) was 40%, which was field capacity water content (m^3 m^{-3}); the minimum soil water content corresponding to minimum soil water storage capacity (S_{min}) was 30%, coming from the wilting point; and the average first soil layer depth was 20 cm. Thus, *Sm* (maximum soil water storage in the upper soil layer) was fixed at 20 mm (10% x 20 cm). After several optimization runs for calibration, the *fo* and *fc* values that minimized the absolute sum of errors were 50 and 34 mm h^{-1} respectively. Total runoff for calibration was 61 mm coming from random 14 out of 27 rainfall events. The total observed runoff from validation events (13 rainfall events) was 45 mm and the estimated value was 43 mm (2 mm error).

Fig. 2.6 shows an example of one rainfall event in 2012 where runoff is simulated (dot line from smoothed simulation by moving average) as the excess rainfall when soil infiltration capacity (solid line) is lower than rainfall intensity. The non-continuous line represents the rate of observed runoff on the 5 min time scale but represented as mm h^{-1} in order to match scales.

Application of this infiltration model gave an acceptable estimation of total runoff per rainfall event (as rainfall excess) based on rainfall dynamics.

The 27 observed and estimated runoff events were classified in six runoff depth classes (< 2, 2-4, 4-6, 6-8, 8-10 and >10 mm runoff) according to data frequency. All classes were very similar in cumulative distribution when simulated and observed runoffs events were plotted (Fig. 2.7). However, for low runoff conditions, (close to 1 mm) the model tended to underestimate runoff (zero runoff) most of the time.

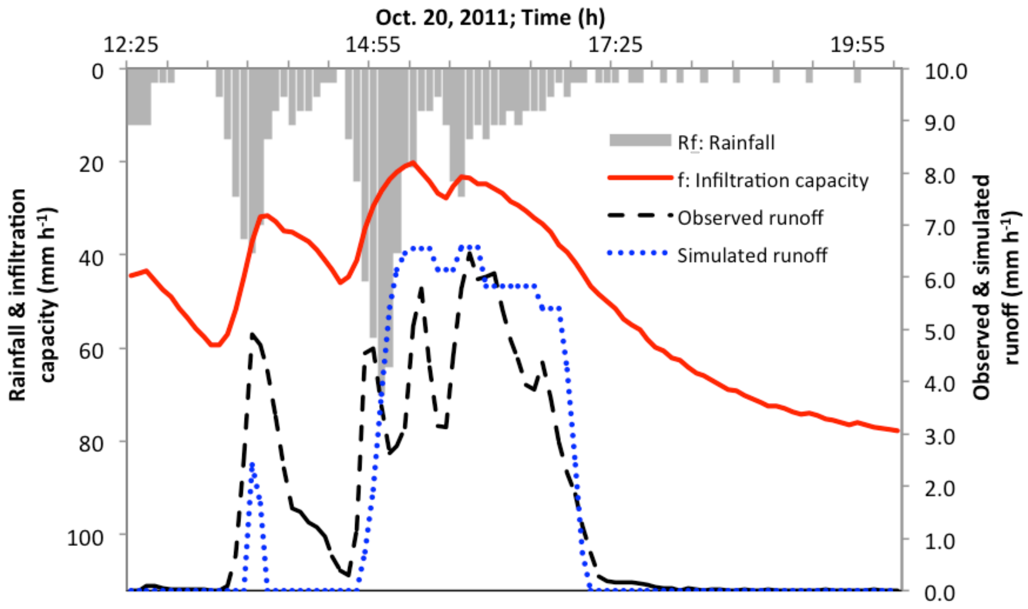

Figure 2.6. Hyetograph of a rainfall event on October 20th, 2011. Observed rainfall (Rf), infiltration capacity (f) and observed runoff (12.6 mm). Simulated runoff (12.6 mm and smoothed) by the Diskin and Nazimov model corresponds to the rainfall excess denoted by a rainfall bar cut by infiltration capacity (f).

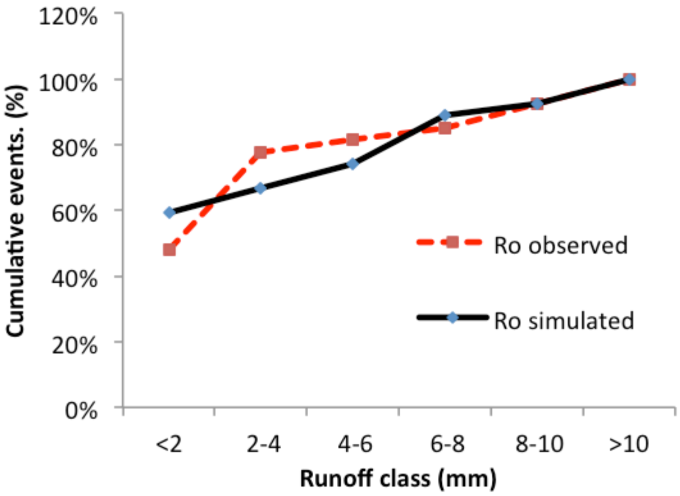

Figure 2.7. Cumulative percentage of observed runoff events (Ro observed) and simulated runoff events (Ro simulated) classified by total runoff depth event category (mm).

2.4. DISCUSSION

2.4.1 Annual runoff and soil loss

The average measured runoff each rainy season was 63 ± 36 mm, similar to the values reported by other studies under similar shade coffee systems. Ataroff and Monasterio (1997) measured 87 and 97 mm of runoff in two rainy seasons (1750 mm rainfall each). Vahrson and Cervantes (1991) measured a 27.9 mm total runoff depth in one rainy season (2092 mm rainfall). However, Gómez-Delgado (2010) measured runoff of less than 1 mm for a partial rainy season, with 938 mm of cumulative rainfall on a 20% soil slope, but in volcanic (sandy) soil with a very high infiltration capacity.

The average annual soil loss was around 1 t ha^{-1} yr^{-1}, which can be considered as light for cultivated lands according to FAO (1979). Other studies reported similar low erosion rates under permanent cultivate systems such as forest with 19 to 29 kg ha^{-1} yr^{-1} under 70% slope approximately (El Kateb et al., 2013) or Tapia et al. (2002) that reported 0.2 to 0.6 t ha^{-1} yr^{-1} under no tillage management plus residues. However, even when there are no data for soil formation on the site, the on-site and off-site consequences of soil erosion and the value of this soil loss are still relevant. For a coffee plantation with a similar soil texture (50% clay) and slope (60%), Vahrson and Cervantes (1991) reported erosion rates of 0.17, 0.34 and 1.4 t ha^{-1} yr^{-1} for no-shade coffee, pasture and shade coffee land use respectively. Verbist et al. (2010) found between 4-6 t ha^{-1} yr^{-1} soil loss from established (good soil litter accumulation) coffee plantations on a 70% slope. Attarof and Monasterio (1997) measured different soil losses of between 0.39 and 6.62 t ha^{-1} yr^{-1} in two consecutive years with different coffee plantation ages and systems on a 60% soil slope. On a 20% soil slope, Gómez (2010) measured 0.03 t ha^{-1} soil loss on a plot scale under shade coffee over one rainy season. Also, Iijima et al. (2003) measured 3.2 t ha^{-1} yr^{-1} on a 27% slope under coffee in Sumatra. Thus, highly variable soil loss values have been reported so far for coffee under similar slope conditions with soil type and management appearing as main factors explaining variations.

The moderate annual soil loss observed in our study falls within the range of the reported values and can be related to the systematically low sediment concentration compared to values reported in the literature (Presbitero et al., 1995; Verbist et al., 2010). The mean sediment concentrations measured for the three highest rainfall event depths (124, 100 and 92 mm) registered over the three years were 1.42, 1.64 and 1.62 g l^{-1}. In addition, correlations between sediment concentration values and rainfall characteristics under our study conditions were very low, which is different from the results obtained by Assouline and Ben-Hur (2006) or Ribolzi et al. (2011), who found that sediment concentration increased with cumulative rainfall event simulated in the laboratory. Even more, no significant increment in sediment concentration was observed as runoff increased under extreme rainfall events. Five factors might explain this trend of low soil detachment: (i) less effective rainfall per area due to a steep slope which allowed to capture around 85% of total rainfall per area; (ii) a high coffee density, above six thousand plants per hectare, which, together with the addition of shade trees, effectively protected the soil surface from the impact of high energy raindrops; (iii) a very good soil coverage over the entire rainy season, even when weeds were controlled, since cut plants were left over as coverage, added to previous materials such as coffee leaves and branches; (iv) the presence of micro-terraces which segmented the total plot length therefore the soil aggregates transportation, thus less opportunity for aggregates or soil particles breakdown as Wang et al. (2014) shown. (v) a good soil infiltration capacity observed even during extreme rainfall events. This almost permanently high infiltration capacity can be itself explained by the combination of a good soil coverage and a fairly good aggregate stability for this soil (Mean Weight Diameter= 1.5 mm) (Nespoulous, 2011) preventing surface structure degradation and crust formation. This was observed by Truman et al. (2005) on an Ultisol with Black oat (*Avena strigosa* Schreb) where infiltration was around two times higher under no residues removal, no till and paratill compared with residues removal, conventional till and non-paratill. The relevance of aggregate stability (Wang et al., 2014) and crusting on soil erosion in Ultisols (subtropical China) was shown by Shi et al. (2010) and Yan et al. (2008) under bare soil. All these factors combined contribute to a very low soil detachment, that allows keeping erosion under a moderate level, considering steep slopes and significant rainfall observed in the area.

2.4.2 Seasonal and inter-event dynamics of runoff and soil loss

Surface runoff and soil loss showed a strong seasonality with a critical period lasting from September to October. Since we observed a quite constant sediment concentration, soil loss dynamics strongly followed runoff dynamics, which can be explained by a combination of soil water content and rainfall dynamics. In fact, the accumulation of rainfall during the rainy season and the more continuous rainfall events in October allowed higher initial soil water content and runoff rates.

The general rainfall trend was similar for the three years, with the beginning of the rainy season in May and the highest monthly rainfall from August to October. However, relatively dry conditions were observed in 2012 that affected runoff and soil loss behavior for 2012, as well as for 2013: a large soil water storage deficit was observed towards the end of 2012 and this condition was inherited in 2013. The average monthly soil water content at the beginning of the 2013 rainy season (Fig. 2.3) was 27.3% for W30 whereas it was 36.3 and 31.3% for 2011 and 2012 respectively. This shortage in soil water storage delayed the start of surface runoff during the 2013 rainy season (Fig. 2.3 and Fig. 2.4). In addition, a wider spread of rainfall events throughout the rainy season occurred in 2013.

Our study, based on three years of monitoring, allowed showing this inherited soil water content effect on year after year runoff-erosion variability. In fact, reporting soil erosion rates from shorter periods (< 2 years lap) could result in missing this important dynamics.

Despite the good overall correlation between rainfall and runoff at inter-event scale, also reported in other studies (López-Bermúdez et al., 1998; Descroix et al., 2002; Descheemaeker et al., 2006; Verbist et al., 2010) the rainfall depth had a strong relationship with runoff and soil loss where rainfall intensity is highly correlated with runoff and soil loss normally (Vahrson and Cervantes, 1991). It seems good soil coverage by litter, coffee and shade trees protected the soil from high kinetic energy rainfall drops and the effect of a homogeneous or concentrated path runoff flow became relevant under this coffee system and slope conditions. This good soil coverage has been observed in soil erosion studies (Truman et al., 2005; Anikwe et al., 2007; Zhou et al., 2013) as very effective to reduce runoff production and soil detachment. Furthermore runoff coefficients per event generally increased over the rainy season, explaining the seasonal runoff dynamics. However, these runoff coefficients remained relatively moderate, even during the main runoff period at the end of the rainy season. The mean monthly runoff coefficient was always lower than 10% in October each year. There were only very few significant runoff events in October 2011 and 2012, with a runoff coefficient exceeding this value, whatever the mean rainfall intensity of the event. This means that the mean infiltration capacity of the plots was high. The high and almost constant soil coverage throughout the rainy season undoubtedly largely explained this result. However, a more detailed analysis of the intra-event runoff dynamics would provide a clearer understanding of the actual infiltration properties and the interactions between rainfall intensity, soil water content and infiltration that explain runoff behavior.

2.4.3 Intra-rainfall event dynamics of runoff and soil loss

The inter-event analysis showed that the initial soil water content was essential in explaining the runoff behavior. The fixed threshold of rainfall depths to start runoff estimated from data used for Fig. 2.5 in the inter event analysis underestimated the runoff per rainfall event since it did not take into account this dynamic infiltration capacity as rain fell and rainfall intensities changed. However, this soil water content changes with the rainfall-infiltration dynamic, in a relatively complex way. The Diskin and Nazimov infiltration model simulates these interactions and was just used as a tool to determine if the intra-event rainfall pattern and soil water content explained runoff better than inter-rainfall data. It only used soil water content at the beginning of the rainfall event along with the rainfall depth for each time lapse (5 min) to simulate the water dynamics within the soil profile and their resulting effects on rainfall infiltration.

This model was very theoretical but fitted well enough with the runoff observed in the field. The rainfall intensities and the initial soil conditions were the main factors that explained runoff variability at intra-event level. The fact that rainfall intensities above 40 mm h^{-1} were those that best fitted the model could mean a specific condition in the field that changes runoff drastically at those rainfall intensities. One possible explanation is the litter present along the coffee alleys. This litter could work as a uniform organic rug that intercepts rainfall and might allow faster infiltration (Truman et al., 2005) into the soil and protect from soil crusting formation caused by rainfall kinetic energy (Zhou et al., 2013). However, when rainfall intensity becomes higher (>40 mm h^{-1}) most of the rainfall film might move over the litter as a hortonian flow and runoff could increase drastically.

The latter demonstrated that the rainfall intensity pattern was more relevant to explain surface runoff rate than that observed from correlation coefficients in the inter-event analysis where correlation with runoff, sediment concentration and soil loss were very low. At inter-event scale the rainfall intensity was estimated as average for the whole event and had low correlation with runoff and soil loss, however when intensities over a rainfall event were taking into account for estimation of soil infiltration changes and runoff changes as well, they became useful by using the Diskin and Nazimov infiltration model. Nevertheless the model did not fit right all the time, even showing a right pattern as rainfall varied on intensity. The model was susceptible to soil water initial conditions; soil water storage capacity and how large was the highest and lowest soil infiltration capacity (fc and fo).

However, even when the infiltration model followed the changes on runoff as infiltration changed due to rainfall recharge to the soil water storage and the effect on producing excess rainfall, under some events the estimated infiltration capacity was higher than observed with right pattern but off the scale. The model could be improved (more complex) but that was out of this paper´s objectives.

Explanatory variables that might explain the remaining discrepancy between data and modeling could be: 1- The rainfall plot interception area where runoff came from could be lower than the assumed total plot area and perhaps only part of the bottom plot area contributed to runoff registration and the contributions of the interception plot are increased as soil water content augments. This was observed and measured by Ghahramani and Ishikawa (2013) on smaller plots (30 m^2). 2- The decrease in heterogeneity due to large plots was not as much as expected and affected data variability where differences in micro-surface, depressions, soil depth layers and plant distribution had a strong effect on runoff distribution. 3-The runoff concentration arising from stem flow (shade trees) could be relevant if they are adjacent to border plots and that flux might not disperse easily around the tree, and the metallic wall allowed runoff concentration as a channel. The latter about stem flow runoff contribution was pointed out by Charlier et al. (2009) and Cattan et al. (2009); and, 4- The simple Diskin and Nazimov model considers water dynamics in only one soil layer. In reality, the water dynamics in the upper layer may depend sometime on this layer, and sometimes on water logging that comes upward from deeper layers. To simulate such dynamics would requires much more complex modeling, applying Richards' equation (Richards, 1931) to different layers, which was not possible within this research.

2.5. CONCLUSION

This study of runoff and soil loss on a plot scale under a coffee plantation on a steep slope showed that the mean annual erosion rate under these conditions was about 1 t ha^{-1} yr^{-1}. This moderate value is related to the low and relatively constant sediment concentration (about 1.3 ± 0.3 g/l), whereas the surface runoff rate showed a strong seasonal pattern with low values at the beginning of the rainy season and maximum values during October. The good soil coverage observed throughout the rainy season plus the presence of old micro terraces contributed to efficiently decreasing the erosion rate. The good soil coverage probably explain why we measured erosion rates consistently lower that what was reported by other authors on Ultisols working on bare soil, where cultivation practices and low aggregate stability produced soil crusting. .

A particular critical period (October) over the rainy season was the source of more than half the soil loss and runoff registered for the whole season. Soil water content dynamics played a very important role in these surface runoff-soil loss observations. Furthermore, soil water storage status inherited from previous year has an important role in surface runoff production during the rainy season of the following year. As the soil profile had less water stored, reaching water saturation on superficial layers was difficult thus less runoff production. Runoff and soil erosion studies at plot scale lacking of soil water content measurements (at least superficial) might induce incomplete conclusions since that variable is an important driver for runoff production.

Inter-event surface runoff and soil loss variability was highly correlated with rainfall characteristics (especially rainfall depth) and soil water content, but not with rainfall intensity due to good and almost constant soil coverage over the rainy season. However, the intra-event analysis showed that runoff and soil loss occurred only during short periods of time within the rainfall event. These transient runoff periods corresponded to rainfall intensity values above an infiltration threshold that changed depending on the superficial soil water content and were linked to water status in deeper soil layers not taken into account in the Diskin and Nazimov model. Thus a more complex infiltration model should be used in order to estimate runoff in those conditions.

Thus, most of the effort in controlling runoff and erosion should be focused towards this period in order to ensure that soil coverage remains high and field micro-terraces are present and in good condition. This allows more rainfall infiltration above this threshold and prevents runoff and soil loss increments. In the event of weed control prior to harvesting, it should be as far as possible towards the end of the rainy season (November) where soil water content has decreased and rainfall is more dispersed.

Chapter 3. Runoff and soil loss under four coffee managements on steep land (Ultisol) and tropical conditions, Costa Rica

Abstract

Soil erosion was evaluated after the application of different modifications to shade coffee management, looking for a change in soil loss at plot scale. In 2012 one treatment was established as a reference, consisting of hand weed control (mechanical, by machete), mini terraces renewal and common shade tree pruning done by local coffee producers. Then, three treatments were applied on six of the eight plots used for runoff since 2011. The treatments were: no renewal of mini-terraces (NT), herbicide weed control (H) and reduced pruning on shade trees (RP).

The dependent variables: superficial runoff, sediment concentration and soil loss ratios (reference plots as a baseline) were compared for three periods. Period 1 refers to data one year before treatment applications. Period 2 corresponds to the next two months after terraces were renewed. Period 3 covers the year after treatments were applied, and after a two month's transition. Superficial (15 cm depth) soil water content status when rainfall events started was used for grouping and comparing ratios between periods.

The annual runoff of reference plots were 74 mm, 38 mm and 25 mm in 2011, 2012 and 2013 respectively, due to renewal of mini terraces and dry year conditions. The annual sediment concentration was relatively constant among all treatments during the three years (Min.: 0.99 ± 0.50 g l^{-1} and Max.: 1.58 ± 0.52 g l^{-1}) with low variation and a slight tendency to decrease in 2012 and 2013. Soil loss also decreased from 2011 on for the next two years in all treatments (Reference plots had 1620, 784 and 514 kg ha-1 for 2011, 2012 and 2013 respectively).

We found higher runoffs and sediment concentrations when mini-terraces were renewed (Monthly sediment concentration moved from 1.27 g l^{-1} in September to 1.91 g l^{-1} in October in reference plots) and the effect decreased after this transitional period 2 but was still present in period 3, related do dry year conditions. Chemical weed control did not show a clear trend in any of the dependent variables. The reduced pruning treatment reduced runoff, sediment concentration and soil loss in P3 for superficial soil moistures between 30-35% where most observations were collected.

Overall, the most consistent treatment effect was the decrease in erosion under reduced pruning; however, collecting more observations with rainy years would improve the analysis of the effect of those treatments.

Keywords: *steep slope, soil erosion, sediment concentration, runoff, shade coffee, weed control, coffee management, mini-terraces, shade tree pruning*

3.1. Introduction

Coffee crop systems under steep lands could generate high rates of runoff and soil erosion not just with on site effects, but also with significant off site effects related to transference of sediments and associated pollutants (Verbist, 2010; Cannavo, 2011; Blake et al., 2012). However, alternative coffee practices could reduce water runoff and sediment concentration and thus soil erosion. Several studies show that modifications in crop management had significative effects on superficial runoff and soil loss (Presbitero, 1995; Afandi et al., 2002; Thomaz, 2009; Valentin et al., 2014). The practices and processes involved for soil erosion's reduction are: more soil coverage, both from coffee and shade trees that intercept rain drops and decreases kinetic energy; weed roots that maintain the soil, prevent sediment detachment and improve superficial soil porosity thus infiltration capacity; residues that decrease runoff's flow velocity; terraces that increase rainfall infiltration, increase slope heterogeneity and slow down superficial runoff. All these processes are influenced by soil heterogeneity that complicates the analysis, thus larger plots are preferred looking for an integration of heterogeneity. However, it is more difficult to build up several repetitions of large plots.

In a comparison between forest and young coffee (ancient forest area) soil macroporosity and changes in infiltration capacity were measured by Dariah et al. (2004). They observed that runoff increased up to almost five times on 3 year old coffee plantations compared to forest, but decreased as coffee plantations got older and similar to forest measurements.

Changes in soil coverage could have an important effect on runoff for coffee plantations on steep slopes. Many studies have found increments on runoff as the soil coverage decreases (Widianto et al., 2004; Thomaz, 2009; Xu et al., 2013; Zhu, 2014; Descheemaeker et al., 2006; Labrière et al., 2015). Descheemaeker et al. (2006) measuring superficial runoff from small plots (10 m^2) found that vegetation coverage explained 80% variations in superficial runoff through an exponential decay function where runoff became negligible as soil coverage was > 65%. Also, on lower soil coverage Northcliff et al. (1990) reported that soil coverage >30% but well distributed provided protection enough to the soil so that superficial runoff became very low.

Soil detachment and transportation is also decreased by soil coverage (Podwojewski et al. 2008). Mohammad & Mohammad (2010) found a significant change in water runoff and sediment loss under different soil coverage. When natural vegetation (mainly the shrub *Sarcopoterium spinosum*) and forest were tested, the runoff and soil loss was very low compared with cultivated land, deforestation and natural vegetation with *s. spinosum* removed. The effect of coverage is not limited to rainfall interception, but also plant roots penetration improving porosity (Gyssels et al., 2005), organic matter to soil which helps soil structure (Casermeeiro et al., 2004) and infiltration capacity (Hairiah et al., 2006; Mohammad and Mohammad, 2010).

Soil coverage could be increased not only by natural vegetation but also by incorporation to the litter of vegetative materials. The main sources of these materials on coffee systems are branches and leaves from shade tress and coffee plants after pruning (Hairia, 2004; Gómez-Delgado, 2010; Meylan, 2013).

Rainfall characteristics play an important role on producing runoff and soil loss. Its effect could easily complicate any analysis of treatment`s effects due to the interaction of their affected processes. From one year to another, the variation in the rainfall effect was reflected in changes on runoff and soil loss. One way to deal with this interaction between rainfall and treatment could be using ratios between treatments dependent variables and a baseline not influenced by treatments. By doing it this way, the temporal effect of rainfall is removed from one period to the other.

The soil slope can be modified locally (coffee row) by decreasing terrace's flat section slope, which would decrease runoff potential. A practice often used in coffee plantation on steep land is mini-terraces that also provide easy walking trials. These terraces decrease most of the superficial runoff compared with cropland under rainfall events with a recurrence interval greater than 10 years (Paningbatan et al., 1995; Zhu and Zhu, 2014). Another example is from Kothyari et al. (2004) in India that obtained from 1998 to 2001 a low runoff coefficient (Max. 1.5%) and soil loss (0.06-0.42 t ha^{-1} yr^{-1}) on rainfed agriculture (small terraces system) on a 41.4% soil slope and a 75% of surface coverage.

Weed control in coffee is performed mainly in two ways: mechanical or chemical. The mechanical weed control by machete consists in cutting the weeds as low as possible close to soil surface. The chemical weed control is using herbicides such as Paraquat as a non-selective one. The latter is preferred just before the first coffee harvesting since it cleans the soil surface and it is easier to collect coffee grains that fall on the ground. Afandi et al. (2002) measured runoff and soil loss on coffee plantations where weeds were removed, left over as selective weed type or leaving all weed present and having it controlled by mechanical means. They found between 7% and 15.9% runoff (up to 22.7 t ha^{-1} yr^{-1}) on plots clean of weeds and that it decreased as the coffee canopy was increasing year after year; in coffee with weeds the runoff decreased to almost zero %. Blavet et al. (2009) in French Mediterrenean wine growing areas and calcareous soils, measured an increase of soil loss and runoff when chemical weed control was performed.

Coffee crop practices such as pruning; herbicide and mini terraces have not been tested on coffee systems by measuring soil erosion effects. Most of the investigation in soil erosion and coffee crop has been by comparing shade and sun coffees (Varhson and Cervantes, 1991; Ataroff and Monasterio, 1997; Harmand et al., 2007; Siles et al., 2007; Gómez-Delgado, 2010; Verbist et al., 2010; Solano, 2010; Cannavo et al., 2011), by shade trees varieties (Bermúdez, 1980), by coffee age (Widianto et al., 2004) and by different coverage along the coffee alleys (Afandi et al., 2002; Iijima et al., 2003; Dariah et al., 2004; Thomaz, 2009).

We assume that changing coffee cultivation practices can be the most efficient way to increase the provision of clean water to downstream users. If we can estimate the change in erosion related to these improved practices, this can form the basis of a system of payment for ecosystem services adapted to coffee production, accompanied by proper monitoring of coffee practices. It is probably much more realistic to encourage changes of practices on coffee production in this region, than to encourage changes of crops, like afforestation, as is currently the case, with insignificant adoption.

The main objective of this investigation was to determine the effect in terms of superficial runoff, sediment concentration and soil loss of changes in shade coffee management practices. The selected management changes were the use of herbicides, changes in shade tree pruning, and the renewal of mini-terraces.

3.2. Material and methods

The same runoff plots installed since 2011 were used for treatment application. Two plots where selected per treatment choosing one plot from the downhill group and another one from the uphill group, randomly into each group.

Soil erosion variables (runoff, sediment concentration and soil loss) measurements continued the same way they were taken in 2011. The surface soil coverage and coffee coverage were evaluated visually the rainy season in 2013. Also leaf area index (LAI) for coffee and shade trees coverage were measured.

Treatments, measurements and data analysis are described in the next sections.

3.2.1 Plots and treatments description

The experimental site and runoff plots set up are the same as described in chapter 2 since the only difference for treatments was a modification of one of the typical practices the producer applies in his plantation. The measuring time comprehended from July 2011 to November 2013 and covered three rainy seasons.

Three alternative management treatments were applied beside the reference described in more detail in Table 3.1. The reference was looking for the common management system a coffee producer follows around the zone. Then, the mini terraces that were not renewed, weed control with herbicide only throughout the year and reduce pruning pressure that left more shade trees branches.

For all treatments except NT treatment the terraces riser were rectified becoming steeper, terraces flat zone turned flatter and longer compared with its original shape. This could decrease superficial runoff due to flatter terraces and higher slope heterogeneity; however erosion could also increase because terraces become uncovered and splash erosion would be easier to occur. The increment on soil detachments would produce more sediment concentration over a transition period. The no terraces renewal treatment (NT) was expected to produce higher runoff compared to all other plots were this practice was refreshed assuming the low to null coverage and steeper riser effects would be stronger than the slope reduction on flat segment.

When decreasing the intensity of shade tree pruning, a complex effect was expected: in a transition period, a lower coverage of the soil by branches and leaves was expected to produce lower soil protection against runoff and erosion. However, with more remaining branches, we expected the trees to produce more biomass overall, and thus to produce higher quantities of residues at the second semiannual pruning, and protect the soil better altogether.

The weed control with herbicide only could increase soil erosion since live vegetative soil coverage would decrease as it was observed by Podwojewski et al. (2008) thus more runoff would be produced. This increase in superficial runoff would have a better opportunity to detach superficial soil that is not longer helped by weed roots retention. The coverage is also altered by the reduce pressure on shade trees pruning that leave more branches (double than reference plots) in the shade tree. This change would augment the tree coverage therefore more rainfall interception and less rainfall effect on soil surface. The contribution on organic matter from branches and leaves for next period pruning will increase soil coverage, thus more water retention on soil due to less evaporation, but shade tree evapotranspiration should increase. In general, a reduction of runoff, sediment concentration and thus soil loss were expected.

Treatment application started at different times over 2012 due to the producer management program. The first treatment application was reducing pruning intensity (beginning of May) followed by increased herbicide application (August 23rd) and terraces (Sept. 18-25th) at last. The mini-terraces renewal was considered a common coffee practice even when its application is every 4-6 years. Table 3.2 shows a more detailed schedule for these practices for the three years in a row and arranged by treatments.

Table 3.1. Coffee management treatments description. All treatments are base on the reference with one modification per treatment.

Treatment	Description
Reference (Ref)	Coffee pruned branches left on the field perpendicular to slope and hold by coffee trunks. Mechanical weed control twice a year and only one herbicide application just before harvesting. Between 3 to 4 small branches left on shade trees after pruning twice a year. Manual mini-terraces renewal (correction by shovel) in all the alleys along the plot.
No mini terraces renewal (NT)	Same as reference, but mini terraces were not renewed. Additionally, new coffee pruned branches were removed from the plots. However shade trees (*Erythrina sp.*) pruned twice a year were left over the alleys.
Herbicide (H)	Same as reference, but weed control was performed with herbicide (Paraquat contact herbicide) only.
Reduced pruning (RP)	Same as control, but instead of leaving 3-4 branches on shade trees after pruning, 6 to 8 branches were left per shade tree.

Treatment acronyms in parenthesis used from now on in the document.

Table 3.2. Coffee management treatment scheme application (2011-2013) for the shaded coffee plots used for runoff and sediment loss. San Isidro, San Pablo de León Cortés.

Treatment/ practice	**Normal shade tree pruning**			**Mechanical weed control**			**Herbicide use only**			**Mini-terraces renewal**		
	2011	**2012**	**2013**	**2011**	**2012**	**2013**	**2011**	**2012**	**2013**	**2011**	**2012**	**2013**
Ref	✔	✔	✔	✔	✔	✔	X	X	X	X	✔	X
NT	✔	✔	✔	✔	✔	✔	X	X	X	X	X	X
H	✔	✔	✔	X	X	X	X	✔	✔	X	✔	X
RP	✔	X	X	✔	✔	✔	X	X	X	X	✔	X

Ref: Reference management; **NT:** No mini-terraces renewal; **H:** Herbicide usage only; **RP:** Reduced shade tree pruning; **✔:** practice was made**; X:** practice was not made

In Table 3.2 the practices were applied the following dates:

- **Mini-terraces renewal**

  2012: September 18-20, 25th
- **Mechanical weed control**

  2011: June 30th, August 29th and September 12-14
  2012: June 15-23, August 23-27, and November 21-23
  2013: June 26-27, September 18-25
- **Herbicide**

2011: September 14th, October 13-14
2012: August 1st, November 20th
2013: July 17th, October 4th

- **Shade tree pruning**

2011: July 16-20, October 21-31, and November 7-8
2012: April 30, May 1-2, September 13th, September 30th, and October 3-5
2013: May 14-19, September 30th, and October 1-4

3.2.2 Measurements

In order to follow any change in soil coverage and compare it with other treatments a visual coverage evaluation (three levels: 1-low; 2-medium; 3-high) was carried out every two-three weeks in 2013. This visual evaluation consists of three levels index for the flat part of the terrace, the riser and also the coffee plants coverage. The visual evaluation was following the same systems described in material and methods of chapter 2. The visual evaluation was taken in three sites independently: only flat part of mini terrace, only in terrace riser and only coffee canopy coverage. Every alley had three points evaluated (close to plot division and in the middle of that alley), thus an average of all the evaluated points per plot represents the estimated coverage.

Leaf area index (LAI) measurements were taken by a LAI 2000 measuring coffee coverage, and shade trees coverage where the latter was useful for following changes in shade trees canopy due to pruning. It is required to have one fix sensor out of coffee shade trees influence and any other shadow coming from other trees or structures. This fix equipment would be the measurements for direct diffused light (overcast or cloudy) without interference. It measures every 10-20 seconds (time lap is possible to adjust) and they will be used for correction of lectures coming from moving LAI sensor measuring in the coffee plantation. Basically, the readings under the shade trees are subtracted to the fix equipment (outside or completely over the coffee plantation) readings, and the result is the corresponding estimated LAI for shade trees. Then, the readings taken under the coffee canopy are subtracted from shade trees readings represents the LAI for coffee. On the field, only one equipment was available most of the time which obliged to take measurements out of shade trees influence every 2 or 3 readings in order to have a confident base control when values under canopy where taken. A modified methodology for sequence of readings shown by Taugourdeau (2010) was used. It consisted in taking 5 consecutive readings when measuring in coffee plantation as follow: one just above coffee canopy, second under coffee canopy close to trunk, third in middle of coffee lines (alley) but in direction to diagonal next plant, fourth again under coffee canopy close to trunk but corresponding to next diagonal coffee plant (following the same direction when coming fro alley reading) and fifth under same coffee canopy close to trunk (in fourth point) but at the other side of the plant (next alley side). The sensor has to be always pointing to the same direction (in this case NW following coffee alleys) for all the readings all over the coffee plantation and all the days' measurements were taken. The sensor has five different lens rings reading independently (7, 23, 38, 53 and 68 degrees), but due to the high terrain slope, readings from the two rings that capture more flat transmittance (53 and 68 degrees) should be removed for LAI estimation according to equipment manual. Comparison of average LAI values between treatments was determined using unpaired t test (Stata 12.1 ®).

The terraces shape after renewal was evaluated: the proportion of flat and riser sections with respect to the terrace total length before and after renewal were measured and compared. This percentage corresponds to the proportion of horizontal length of the terrace riser with respect to the total horizontal terrace length starting from upper border of the riser and ending to the border of flat section of the terrace.

The runoff, sediment concentration and soil loss data were measured as described in chapter 1. Data were split in three periods. Period 1 refers to the 2011 data until the first months of the 2012 rainy season matching to the period of measurement before treatment applications. This period was considered as a base data (reference) for plots treatment, where original variability from replicate plots was captured and could be used as a base comparison against treatment effects. The first effects on runoff and sediment concentration of each treatment were measured for 2012 just after treatments application being mini terrace renewal the last treatment applied, and this transitory period was called period 2 (end of September until November, i.e. the end of the 2012 rainy season). Period 3 corresponds to the data from the 2013 rainy season when treatments should begin having the effects that were intended in terms of superficial runoff and sediment concentration.

There were a total of 597 rainfall events for the three rainy seasons from May to November period in 2011 to 2013. Basically there was no runoff (very low or absent in most of the plots) under rainfall events below 5 mm depth, therefore for analysis purpose in this chapter these small events were removed. 267 rainfall events were thus analyzed.

3.2.3 Statistical approach:

We showed in the previous chapter that the soil erosion processes in these plots are highly correlated to rainfall depth and soil water content. These two factors varied from 2011 to 2013 thus the effect of rainfall pattern was mixed with plot variability. Treatment effects became hard to extract.

The period 1 (2011 rainy season) was used to evaluate the plot variability before treatment application. The differences between plots were captured by the ratio between every plot against the reference plot being plot 1 (uphill), used for plots 2, 3 and 4; and plot 6 (downhill) used for plot 5, 7 and 8. The same plot ratios were calculated for periods 2 and 3.

It was assumed that any significant changes in these ratios in periods 2 and 3 compared to period 1 could be interpreted as a treatment effect. The runoff and sediment concentrations would vary according to rainfall characteristics such as duration, intensities and depth, but assumed to have the same effect on all plots. As they were captured in the reference plots, we considered that the ratios were a way to compare erosion rates taking into account these unwanted factors of variation. As it was demonstrated in chapter 2, the initial superficial soil water content was a relevant variable as well. To study any possible modification of the effects of these two essential variables (rainfall depth and soil water content at 15 cm depth), we used superficial soil water content for group comparison between ratios. Three categories of initial soil water contents were used: less than 30%, between 30 and 35% and higher than 35%; and ratios for these groups were compared using unpaired t test (Stata 12.1 ®).

The ratios for every dependent variable (runoff, sediment concentration or soil loss) per period using reference treatment as a base were estimated dividing the treatment dependent variable value by the reference dependent variable in the same rainfall event. The calculation of the ratio is shown in equation (3.1).

$$Ratio = \frac{dv_T}{dv_{Ref}} \tag{3.1}$$

Where:

Ratio refers to the ratio between dependent variable (dv) for given treatment (T) divided by the same dependent variable in the reference plots (Ref) for same rainfall event. The dependent variables were runoff (Ro), sediment concentration (gl) and sediment loss (SL). The treatments were: no renew mini terraces (NT), herbicide use only (H) and reduce pruning (RP).

The interpretation of the changes in these ratios is directly related to the expected effect of the treatment. Therefore, if ratio gets lower in next period, it means the treatment measurement of dependent variable decreases too. Also for no mini-terrace renewal effect that was applied in all plots but the treatment itself (NT), the interpretation of the ratio change is still the same

3.3. Results

We show first the effects of treatment applications on the state variables they were meant to modify: terraces proportions (ratio of sloppy section with respect to terrace section, i.e. flat plus riser), soil coverage dynamic over the year and average shade tree coverage (LAI as a proxy). We then present the measurements of the target variables: runoff, sediment concentration and soil loss ratios of every treatment with respect to the reference for the three periods. Finally, we present a statistical comparison of ratios means between periods (i.e. period 1 against period 2 and period 1 against period 3).

In 2011 and 2013 the annual rainfall was 2206 mm and 2220, which were close to average of 1990-2009 period (2460 mm +- 407 mm). But, in 2012 annual rainfall dropped to 1778 mm. The last two years corresponded with data collection of low superficial soil runoff. It was still possible to compare most of the ratios under low records in runoff and sediment concentration. The rainfall events greater than 5 mm were chosen in order to estimate the ratios.

3.3.1 Treatments changes in plots

The new mini terraces dimension after they were renewed were measured and compared. Also the visual soil coverage and canopy coverage are shown besides the measurement taken by LAI-2000.

3.3.1.1 Terraces slope shape

Table 3.3 shows the change in proportion of the two segments on terraces (riser and flat area) just before and after the renewal of the terraces in treatment Ref, H and RP. The average length before renewal of top to bottom of terraces was around 150 cm and approximately 100 cm (66.5%) of this total length corresponded to the riser before the rectification. After the renewal that proportion dropped to 85 cm in average. The changes were longer and flatter terrace section and an abrupt transition from riser to flat section that became unstable. This change was still present in period 3. However, some small terraces slides were observed in some plots (Fig. 3.1 B) that could be sources of sediments. Fig. 3.1A shows how a mini terraces looks like before and after it was rectified manually with a shovel.

Figure 3.1 A) Visual aspect of mini terraces renewal (beyond the metallic frame) vs not renewed (before the frame). B) Small terraces slides observed at the end of 2012 and in 2013.

Table 3.3. Proportion of horizontal length of riser section with respect to terrace total length before (Period 1) and after terraces renewal (Periods 2 & 3).

Treat.	Before	SD	After	SD	Δ
Ref	64%	9%	56%	8%	8%
NT	66%	6%	66%	6%	-
H	68%	7%	53%	9%	15%
RP	68%	9%	54%	7%	15%

SD: standard deviation

3.3.1.2 Soil coverage

Soil coverage was evaluated visually and in general the coverage remained high throughout the rainy season (Figure 3.2). The flat section showed almost complete coverage with very small differences between treatments as it can be seen in Fig. 3.2A where the lowest value was around 2.8 from May to October. Leaves, branches and residues from coffee plants and shade trees contributed to most of the coverage in the flat section. The riser section had a different dynamic on coverage (Fig. 3.2B), it increased over the rainy season from all the treatments (Ref, NT and RP) with mechanical weed control, and the recovery was faster than the herbicide treatment. The first herbicide application on July 17th had a longer effect in limiting weed regrow. The second herbicide application on October 4th also had more permanent effect on weed coverage in the riser (Fig. 3.2B).

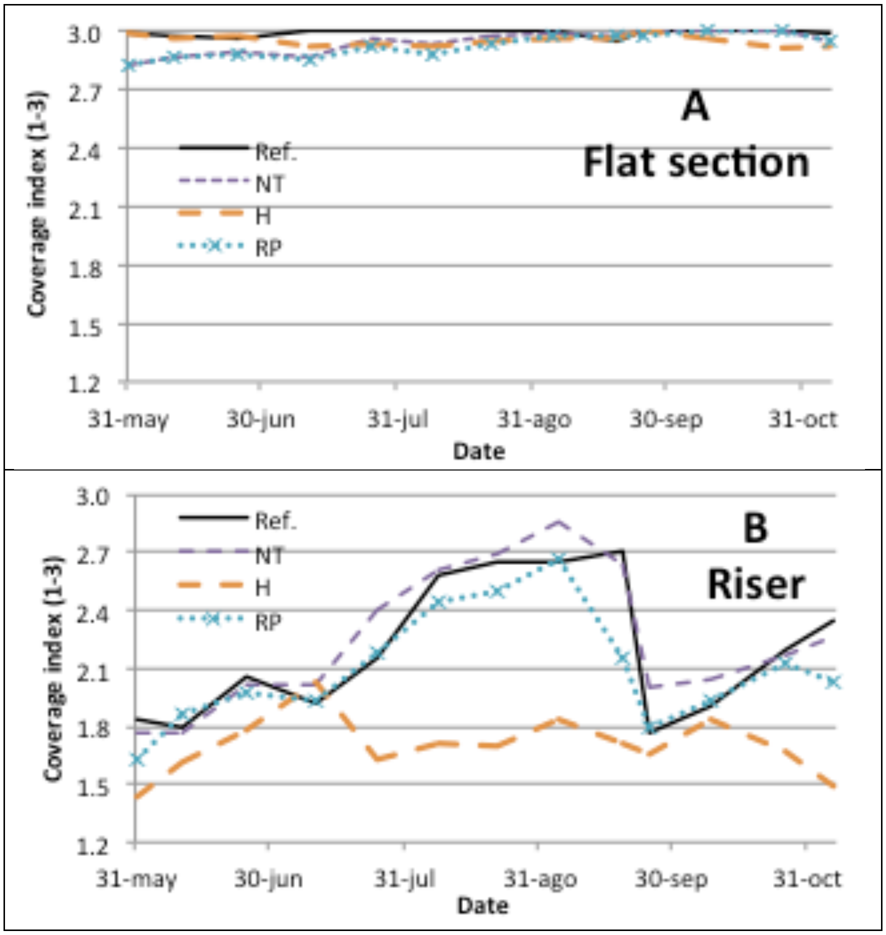

Figure 3.2. Average visual coverage index in 2013 for flat and riser section of terraces per treatment plots.

3.3.1.3 Shade trees and coffee coverage

There were more frequent records from visual coffee coverage compared to coffee and tree LAI measurement made with the LAI2000 sensor. LAI measurements have to be made in conditions of overcast sky, that are only obtained between 5:20 to 6:20 am, or during the afternoon rains. Therefore, the time windows for measurement were reduced. Moreover, some records were lost due to wrong readings from equipment and the lense had to be sent for reparation abroad and took little more than one month. These constraints left few oportunities for LAI measurement.

Fig. 3.3 shows the average shade trees LAI measured before and after pruning. The shade trees from reduced pruning treatment tended to have higher LAI as compared to the other treatments. However this difference tended to decrease after the 2nd pruning of the year (October 3-5), that was not made by our trained worker. The worker assigned by the owner of the plot was afraid to leave too many branches on the shade tree in the pruning treatment and the difference was not evident but RP was still significant different to Ref and NT on September 18th and November 5th. The LAI readings on herbicide treatment were never significant different from RP.

The coffee coverage evaluation in 2013 were: visually (Fig 3.4) and using the LAI 2000 sensor (Fig 3.5). Fig. 3.4 shows how the visual appreciation of coffee coverage was quite constant over the year with some variation. The index a little lower than 2 means the coffee coverage was around 50% but the number is an approximation since the scale was general and qualitative instead.

Fig. 3.5 shows the coffee LAI value, with a mean value of 3.26 (SD: 0.41) with low variation in 2013 (except RP on September 18th). The coffee LAI in RP plots was significant ($P \leq 0.04$) different to Ref, NT and H on September 18th and November 5th. LAI values are similar to the ones Meylan (2013) measured with the same equipment in the same coffee plantation but smaller plots (<10 m^2).

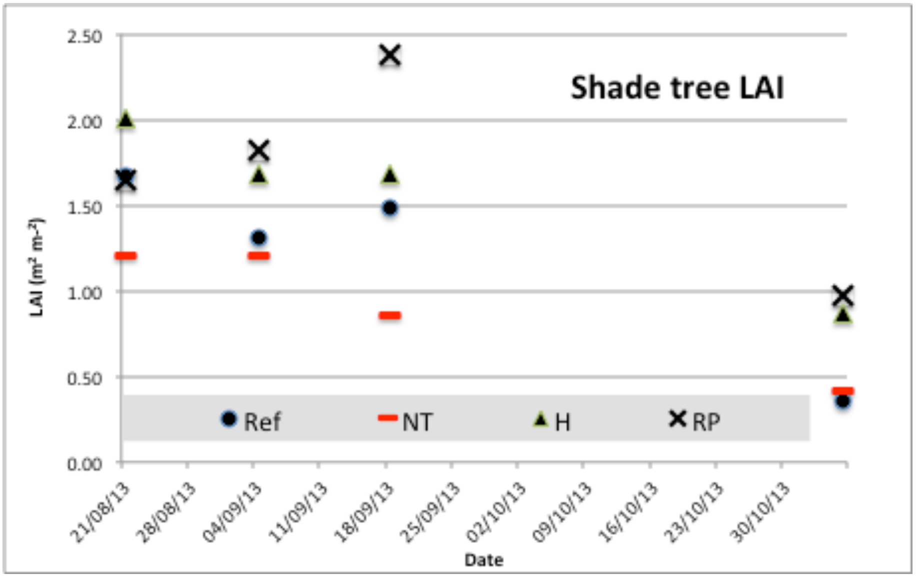

Figure 3.3. Shade trees leaf area index (LAI) before and after 2nd shade trees pruning (end of September). RP LAI index were different from Ref and NT on Sept. 18th and Nov. 5th ($P \leq 0.05$).

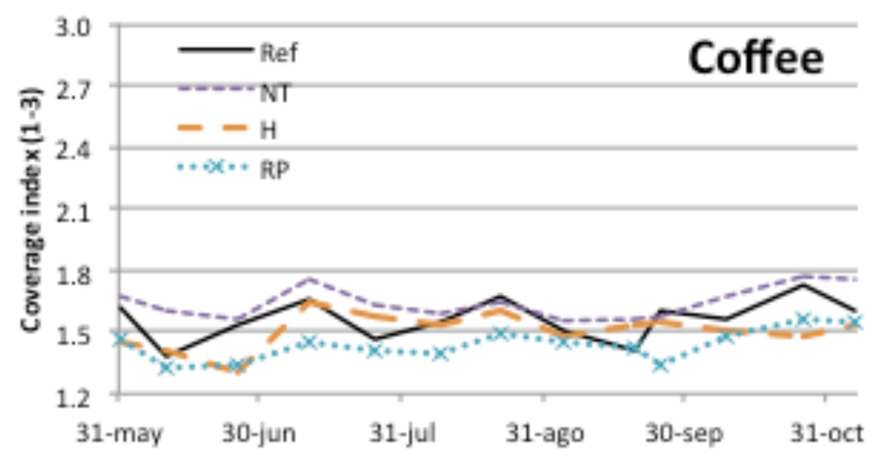

Figure 3.4 Evaluation of visual coffee coverage in 2013 in 8 runoff plots and estimation from three visual evaluation in all alleys.

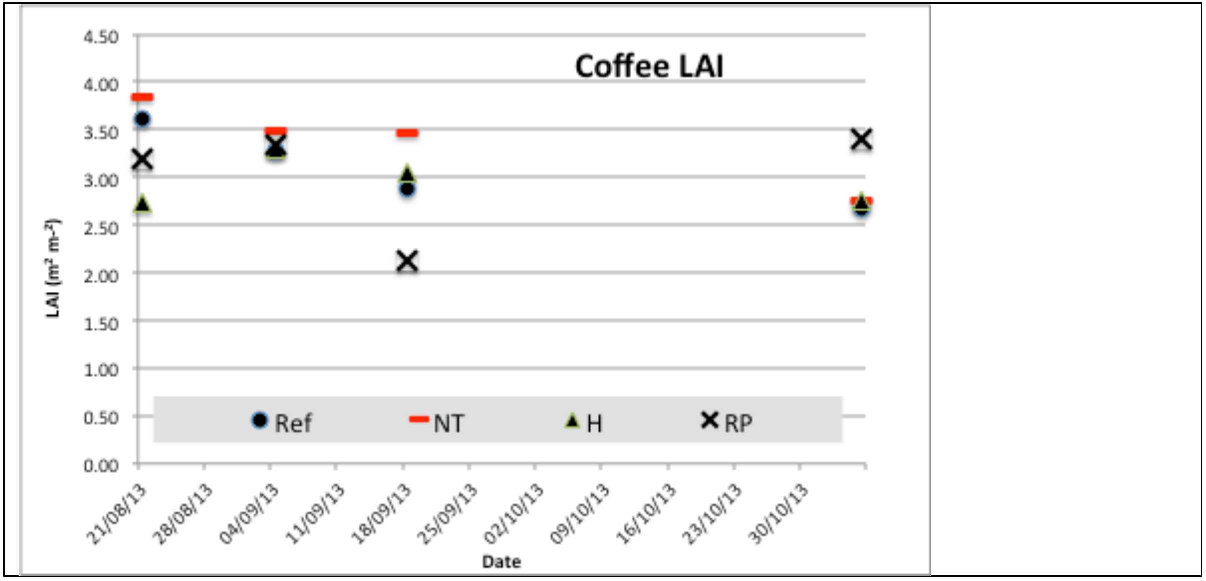

Figure 3.5 Coffee LAI measured with LAI 2000 in 2013. Readings taken between 5:20 and 6:25 am with only one sensor. San Isidro de León Cortés. RP LAI index were different from Ref, NT and H on Sept. 18th and Nov. 5th ($P \leq 0.04$)

The change in terraces dimension were small being more relevant their shape with unstable riser (very steep) and very poor soil coverage. Mini-terrace flat section had good soil surface coverage and stable in the evaluation time. The mini-terraces riser had low increase in weed coverage after herbicide application, which was the contrary on other three treatments with mechanical weed control. Coffee coverage throughout the year was relatively stable when visually evaluated and significant differences ($P<0.04$) were observed between RP and other treatments in the last two LAI measurements. LAI for RP were significant different ($P \leq 0.05$) compared with Ref and NT, but not against H.

3.3.2 Treatments effect on superficial runoff

The occurrence of relatively dry years (low annual rainfall and inherited low soil water storage from previous year) during the period of treatment application complicated the search for big trends.

Table 3.4 has the monthly and annual rainfall for the three years evaluation where a notorious drop in rainfall for 2012 is observed and October that year had very low rainfall accumulation.

Table 3.4. Summary of rainfall for 2011-2013. San Isidro, San Pablo de León Cortés, Costa Rica.

Variable	Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual[+]
Total rainfall (mm)	*2011*	197	303	287	321	271	728	99	2206
	2012	263	221	208	410	289	316	71	1778
	2013	281	343	162	289	495	508	142	2220
Maximum rainfall intensity (mm h^{-1})[*]	*2011*	16	9	12	12	20	20	8	20
	2012	13	14	11	33	6	17	8	33
	2013	7	21	8	17	13	13	10	21

[+]: Total rainfall corresponds to the May-Nov. period.

[*]: Estimated as the total rainfall depth per event divided by the total duration of that rainfall event.

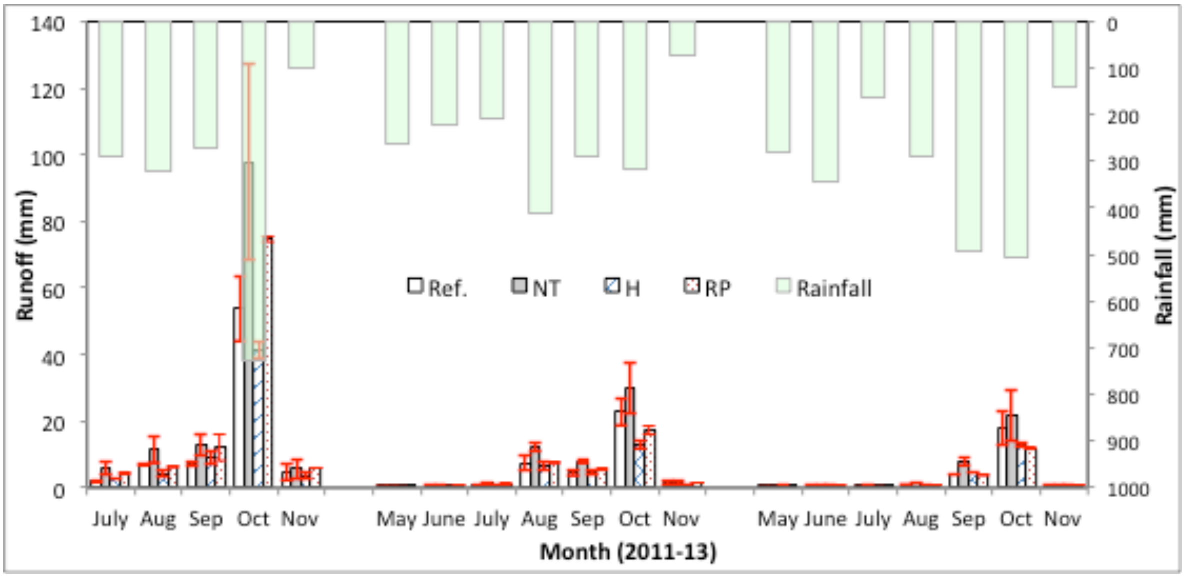

Figure 3.6 Monthly runoff per treatment and monthly rainfall over the three years. Red bars represent +- one standard deviation.

3.3.2.1 Dynamics of runoff before and after treatments

Total annual runoff decreased since 2011 to 2013 despite the annual rainfall recovery in 2013, being similar to 2011. In 2012 the total rainfall was lower than 2011 and 2013 (Table 3.4). The cumulated rainfall in 2013 was similar to 2011 but with less intense rainfalls. The cumulated runoff (numerical data summary in Annex C) in 2013 was around 34%, 24%, 31% and 17% of total runoff in 2011 for Ref, NT, H and RP plots respectively.

Fig. 3.6 shows how the NT plots had always higher runoff compared with the others but the differences got smaller after treatments applications albeit mini terraces were not renewed in NT. RP was the highest in 2011, but decreased in 2012 and even more (proportionally to other treatments) in 2013.

Higher runoff was observed in October every year, making the plots treatment comparison easier. During this month, the order in runoff between treatments varied depending on the period (Figure 3.6): in 2011(Period 1, before treatment application) the order was NT > RP > Ref > H; in 2012 (Period 2, just after treatment applications), the order changed to NT > Ref > RP > H; in 2013 (period 3, one year after treatments application), the runoff order changed again NT > Ref > H > RP but runoff values getting closer to each other. Furthermore the standard deviations seem to get smaller after treatment application.

3.3.2.2 Runoff ratios

The ratios during period 1 describe the relative behavior of all treatment plots, compared to the reference plots, without any actual treatment applied. Somehow, they encompass all the unwanted physical differences between the plots. Then, the objective of our analysis is the evolution of this ratio after the time when treatments were applied, first during a transition period (period 2) and then for a period when we assumed the effects were stronger (period 3, after more than 6 months of the application of the treatments). A ratio increasing from period 1 to 3 shows a treatment that produced more runoff.

NT and RP treatments at medium soil water content (Table 3.5) had significant differences ($P \leq 0.011$) in terms of runoff average ratios between both periods (2 and 3) with respect to period 1. In period 2 all significant ratios decreased, but in NT treatment the ratio increased in period 3 (more rainfalls in period 3). However in RP treatment in period 2 the ratio decreased and it did again in period 3. Herbicide did not present any significant change in terms of superficial runoff for any period.

Table 3.5. Runoff ratios (Treatment/Reference) per period and their respective probabilities when periods were compared (Period 1, 2 and 3). Grouping by three soil water content categories at 15 cm depth (W15).

	NT			H			RP		
W15 (%) ➔	<30	30-35	>35	<30	30-35	>35	<30	30-35	>35
Period 1	**0.85**	**2.34**	**1.64**	**0.72**	**1.03**	**1.37**	**1.35**	**2.36**	**1.63**
n	*46*	*131*	*51*	*45*	*102*	*45*	*8*	*70*	*22*
Period 2	**1.00**	**1.04**	**1.28**	**0.83**	**1.04**	**1.30**	**1.40**	**1.49**	**1.41**
n	*6*	*13*	*16*	*8*	*42*	*22*	*46*	*73*	*22*
Difference	*0.15*	*-1.29*	*-0.35*	*0.11*	*0.01*	*-0.07*	*0.05*	*-0.87*	*-0.23*
Probability#	*0.652*	*0.001*	*0.091*	*0.679*	*0.982*	*0.701*	*0.896*	*0.001*	*0.385*
Period 3	**0.94**	**1.84**	**3.71**	**1.18**	**1.23**	**1.45**	**0.91**	**1.09**	**1.02**
n	*67*	*89*	*1*	*67*	*89*	*1*	*68*	*89*	*1*
Difference	*0.09*	*-0.50*	*2.07*	*0.46*	*0.19*	*0.08*	*-0.44*	*-1.27*	*-0.61*
*Probability**	*0.614*	*0.011*	*nd*	*0.071*	*0.192*	*nd*	*0.224*	*0.000*	*nd*

n: number of observations; nd: not enough data for comparison.
refers to probability of means difference between periods 1 and 2.
* refers to probability of means difference between periods 1 and 3.

3.3.3 Treatment effect on sediment concentration

The changes in sediment concentration before and after treatment application and changes in ratios base on periods are presented in this section.

3.3.3.1 Dynamics of sediment concentration before and after treatment

Terraces renewal had an effect on sediment concentration: just after this renewal at the end of September 2012 where sediment concentration increased for a short time (September to October) in Ref, H and RP treatments bars but small change in NT treatments (Fig. 3.7) which maybe is easier to notice from numerical data (Annex C). In September 2012 the gL for Ref, NT, H and RP were 1.27, 1.11, 1,17 and 1.60 g l^{-1} respectively, and gL in October for same treatment order were 1.91, 1.23, 1.61 and 2.16 g l-1 and the gL for NT did not change as much as the others. One year later, in October 2013 the highest treatment was NT and the others dropped the sediment concentration to values similar to 2011.

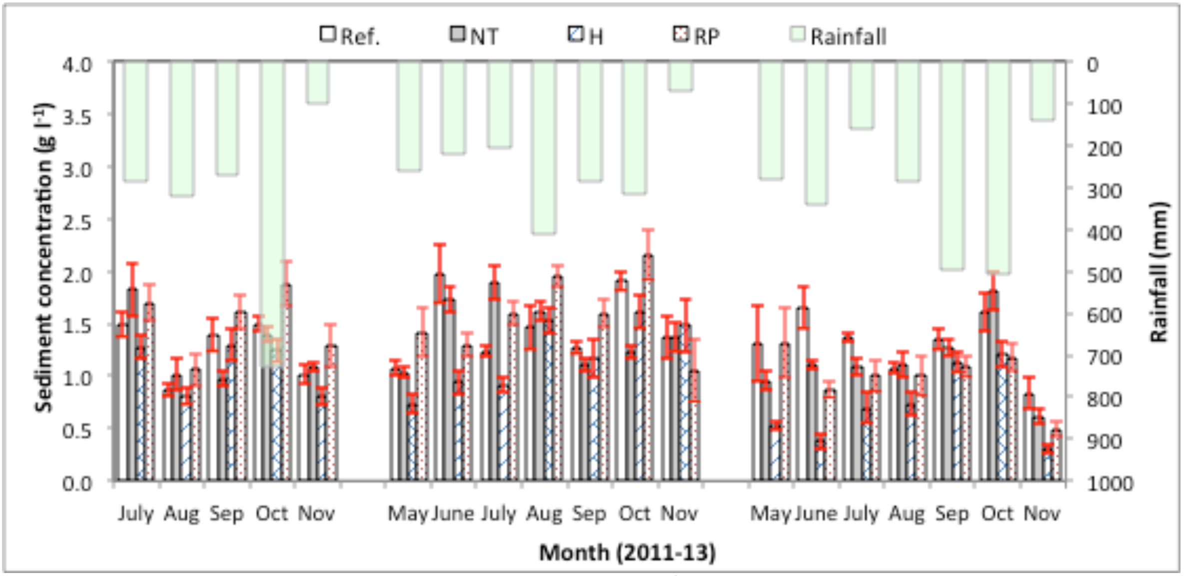

Figure 3.7 Monthly average sediment concentration (g l^{-1}) per treatment and monthly rainfall over the three years. Red bars represent one standard error.

3.3.3.2 sediment concentration ratios

Table 3.6 shows that for NT and RP treatments had significantly lower sediment concentrations in period 3 as compared to period 1 when soil water content > 35%. The lower coefficient ratio for RP means less sediment concentration under RP. The positive ratio change (higher value in period 3) for NT when superficial soil water contents were > 35% means that under conditions close to soil saturation the sediment concentration increased in NT plots in 2013 meanwhile the sediment concentration in other treatments decreased despite more rainfall in 2013.

The treatment H had significant positive change on ratios in period 2 meaning higher sediment concentrations in 2012 just after mini terraces renewal but only significant on very superficial soil.

Table 3.6. Sediment concentration ratios (Treatment/reference) per period and their respective probabilities when periods (Period 1, 2 and 3) were compared. Grouping by three soil water content categories at 15 cm depth (W15).

	NT			**H**			**RP**		
W15 (%) ➔	<30	30-35	>35	<30	30-35	>35	<30	30-35	>35
Period 1	**1.49**	**1.35**	**0.95**	**1.68**	**1.07**	**1.02**	**1.22**	**1.20**	**1.61**
n	*49*	*154*	*52*	*47*	*124*	*47*	*7*	*91*	*46*
Period 2	**1.00**	**1.50**	**0.78**	**0.77**	**1.35**	**2.38**	**1.26**	**1.36**	**0.93**
n	*9*	*14*	*16*	*11*	*44*	*21*	*51*	*77*	*22*
Difference	*-0.49*	*0.15*	*-0.17*	*-0.91*	*0.28*	*1.36*	*0.04*	*0.16*	*-0.68*
Probability#	*0.175*	*0.716*	*0.060*	*0.094*	*0.307*	*0.000*	*0.906*	*0.433*	*0.002*
Period 3	**0.88**	**1.22**	**1.36**	**1.15**	**0.83**	**0.54**	**0.75**	**0.80**	**0.46**
n	*77*	*114*	*3*	*77*	*114*	*3*	*77*	*114*	*3*
Difference	*-061*	*-0.13*	*0.41*	*-0.53*	*-0.24*	*-0.48*	*-0.47*	*-0.40*	*-1.15*
*Probability**	*0.000*	*0.387*	*0.021*	*0.080*	*0.161*	*0.069*	*0.071*	*0.000*	*0.042*

n: number of observations.

refers to probability of means difference between periods 1 and 2.

* refers to probability of means difference between periods 1 and 3.

There were not abrupt changes on sediment concentration over the year, but some trends were observed after treatment application (P2) and effect seems changed the year afterwards. Despite low variability (low standard errors) on measurements this variability seems to maintain low in NT plots except for superficial soil water content > 35%.

3.3.4 Treatments effect on soil loss

The comparison of soil loss between treatments and the changes observed before and after the treatment applications.

3.3.4.1 Dynamics of soil loss before and after treatments

Fig. 3.8 shows how the soil loss in October 2011 had the following order from highest to lowest values: NT > Ref > RP > H. October 2012 corresponds to period 2 where the order changed to RP> Ref = NT > H and finally in October 2013 (Period 3) after one year estabilization, the order changed to NT > Ref >H > RP.

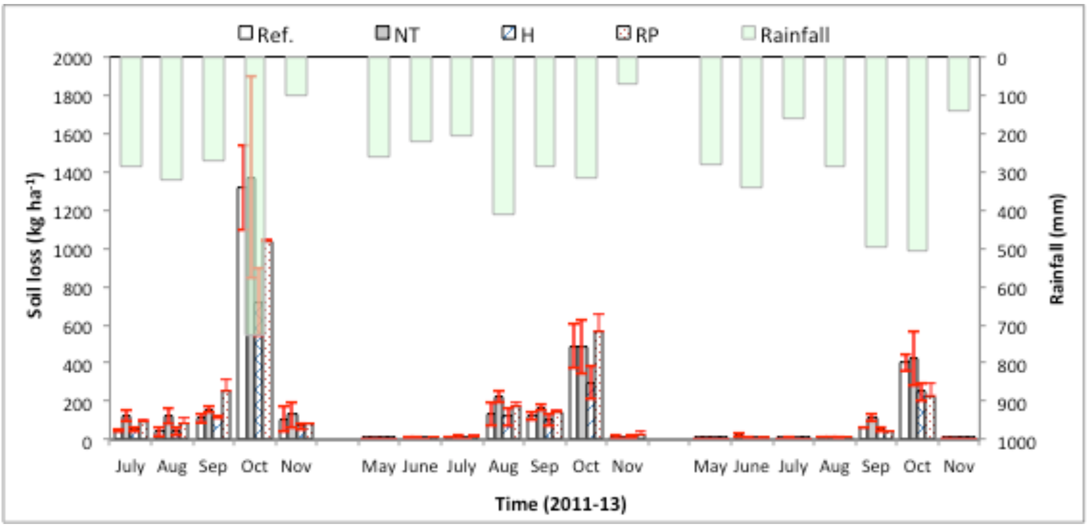

Figure 3.8 Monthly soil loss per treatment and monthly rainfall over the three years. Red bars represent +- one standard error.

3.3.4.2 Treatment soil loss ratios

Ratio analysis shows (Table 3.7) that the only treatments that had significant ($P \leq 0.05$) effect on soil loss reduction were RP practice and NT when superficial soil water content was <30% for NT and 30-35% for RP.

The H treatment did not have any significant effect on soil loss change.

The soil loss from reduced pruning treatment decreased in P3 around half compared to the ratio in period 1 being the only significant change.

Table 3.7. Soil loss ratios (Treatment/Reference) per period and their respective probabilities when periods (Period 1, 2 and 3) were compared. Grouping by three soil water content categories at 15 cm depth (W15).

		NT			**H**			**RP**		
W15 (%) ➔		<30	30-35	>35	<30	30-35	>35	<30	30-35	>35
Period 1		**1.24**	**4.21**	**3.29**	**2.71**	**2.03**	**1.99**	**1.71**	**4.18**	**4.65**
	n	*46*	*130*	*51*	*45*	*101*	*46*	*7*	*69*	*22*
Period 2		**0.85**	**1.29**	**0.92**	**1.53**	**2.09**	**3.45**	**2.48**	**3.05**	**2.04**
	n	*6*	*13*	*16*	*8*	*42*	*21*	*46*	*73*	*22*
Difference		*-0.39*	*-2.92*	*-2.37*	*-1.18*	*0.06*	*1.46*	*0.77*	*-1.13*	*-2.61*
Probability#		*0.643*	*0.368*	*0.467*	*0.564*	*0.945*	*0.078*	*0.612*	*0.386*	*0.2176*
Period 3		**0.70**	**3.05**	**4.83**	**2.12**	**1.65**	**0.72**	**1.80**	**1.85**	**0.73**
	n	*69*	*89*	*1*	*69*	*89*	*1*	*69*	*89*	*1*
Difference		*-0.54*	*-1.16*	*1.54*	*-0.59*	*-0.38*	*-1.27*	*0.09*	*-2.33*	*3.92*
*Probability**		*0.048*	*0.403*	*nd*	*0.645*	*0.597*	*nd*	*0.942*	*0.019*	*nd*

n: number of observations; nd: not enough data for comparison.

refers to probability of means difference between periods 1 and 2.

* refers to probability of means difference between periods 1 and 3.

The soil loss evaluation and comparison only showed a significant reduction in RP when superficial soil water content was between 30-35%. NT treatment had a smaller index in period 3 and soil water content < 30%. The ratio analysis in soil loss was not very informative since many ratios were not significant different

3.4. Discussion

The changes in runoff, sediment concentration and soil loss due to treatments were not strong and not easy to detect but the ratio analysis helps to catch some significant general trends.

The data set was richer in high rainfall and runoff events for 2011 as compared to the following two years. Consequently, the data for after treatment effects were scarce compared with the data available before treatment application and most of these data came from low runoff values. The ratio analysis does not take the absolute values into account, since the ratio reflects only relative changes. Nevertheless, the high variability observed is probably related to these low absolute values commonly associated with high variability (Nearing et al., 1999).

The estimation of ratios among same periods and compared with other periods facilitated interpretation of treatment effects on runoff, sediment concentration and soil loss which controls for rainfall temporal effect.

3.4.1 Effects of treatments on plots surface characteristics influencing runoff and erosion

The three treatments studied had different effects on plots characteristics. The most evident change on soil surface was mini-terraces renewal, which concerned all plots except NT plots. This practice created temporarily unstable and uncovered risers, removes soil surface coverage (litter and weeds) leaving bare soil and disturbed soil particles everywhere under coffee canopy.

The herbicide treatment showed a longer effect on soil coverage reduction. The visual evaluation was very evident at the two times it was applied. The duration of the experiment (only one year and a half) could not be sufficient for the evaluation of the effect, since the soil coverage by litter was still present and this dead material also has an important protection effect (Widianto et al., 2004; Hairiah et al., 2004).

Reduced pruning pressure led to more vegetative material supply to soil surface and higher (than reference) supply of nutrients such as nitrogen improving superficial soil fertility and hence possible more weeds or weeds growing faster.

3.4.2 Effect of treatments on measured Runoff

Compared to the reference, the runoff should have decreased by reduced pruning, and should have increased with herbicide usage and no mini terraces renewal.

The no renewed mini terraces practices had a runoff decrease in 2012 due to lower rainfall events and increased again in 2013 once the rainfall was close to historical average. The terrace renewal in transition period increased runoff since the soil got uncovered, the riser become less stable and uncovered as well and most of the material removed was deposited on the toe or low end of the terrace where runoff could remove it very easy downhill.

Widianto et al. (2004) observed that superficial runoff tended to decrease as the coffee plantation got older (7 and 10 years old), but just after the conversion from forest to coffee crop at 1 and 3 years old coffee had 5 and almost 7 times higher runoff than forest respectively. Our coffee plantation is very old, around 30 years old and has a little bit more than 5000 coffee plants per ha. This coffee system reached its best canopy coverage (only partial changes due to pruning, renovation or desuckering) and shade trees canopy also reached their maturity size and roots have improved macropores, as Dariah et al. (2004) pointed out for mature coffee plantations.

As expected, the herbicide treatment reduced weed coverage for longer periods than mechanical weed control. No clear change in runoff was determined statistically. The presence of litter as soil coverage could help in protecting soil surface from rainfall drops impact and runoff production. A longer-term effect could be necessary to capture any change on runoff.

Reduced pruning pressure seems to be the more evident treatment that affected runoff reduction for periods 2 and 3. It could be a bit daring to assume that mini terraces renewal and reduced pruning could be a good combination looking for runoff reduction. However from ratio analysis, the practice itself (RP) already showed significant effect on runoff reduction. This reduction should be related to more vegetative addition to soil and more canopy protection and rainfall interception.

3.4.3 Effect of treatments on sediment concentration

The concentrations were relatively low, but similar to other studies, with average value around 1.5 g l^{-1} (Bermúdez, 1980; Le Bissonnais et al., 2005). They increased after terraces renewal, particularly in period 2 under herbicide treatment (sediment concentration from 1.17 to 1.61 g l^{-1} after terrace renewal in period 2).

The NT treatment had an increase in sediment concentration in 2013 when rainfall increased as well. A similar situation was observed for herbicide, but not for reduced pruning, which was always lower in sediment concentration for period 3, and the three soil water content classes. The no mini-terraces renewal in NT did not disturb the soil surface, but allowed runoff to move faster which could be associated to higher sediment detachment capacity and transport.

The increase in sediment concentration for herbicide treatment in period 2 and superficial soil water content > 35% was the only significant ratio change for this treatment.

In reduced pruning the sediment concentration moved up from 1.60 to 2.16 g l^{-1}, but decreased in period 3 with highest concentrations (1.32 g l^{-1}) in May 2013 and the rest of 2013 under 1.18 g l^{-1}.

3.4.4 Effect of treatments on soil loss

Even when terraces renewal increased the flat proportion of the terrace, pruning seems to have a stronger effect over the time. Possible explanations of this result could be related to three reasons: (i) higher soil coverage and litter contribution as Hairiah et al. (2006) and Wadianto et al. (2004) demonstrated; (ii) higher canopy coverage from shade trees and (iii) decrease in superficial soil water content due to higher evapotranspiration potential from more shade trees biomass (double of branches) thus less runoff.

From the three dependent variables, SL had only two significant decreases in ratios: with NT and soil water content < 30% and with RP and soil water content between 30-35%. The first would be expected due to high runoff values and relatively high sediment concentration thus high SL, but should be stronger as soil gets wetter which was not the case. This could mean a weak effect. On the other hand, the low soil loss in RP corresponded to the combination of the observed reduction in both runoff production and sediment concentration. This treatment ended as the more efficient (among the applied) and more consistent against soil erosion.

3.5. Conclusions

As any soil erosion study, the high variability in the data was something to deal with all the time, and this variability increases as measured values get smaller which was the case for two consecutive years of data collection (2012-2013) due to below average rainfall amount. However, we had the opportunity to establish a reference from eight plots without any treatment application for one year. This allowed analyzing their “normal” behavior. Using the ratio analysis for the two seasons after treatment application removed the temporal weather effect.

The large size of the plots used for runoff and soil loss measurement was an advantage (compared to more classical 1 m² small plots), assuming that the soil plot heterogeneity was integrated by plot size.

The less conclusive among tested treatment was herbicide as a unique weed control, probably due to high data variability or no time enough to establish its effect. Only two significant effects were observed on SC and SL increase in period 2 just after terrace renewal and under wet superficial soil (>30%).

Mini terrace renewal had three main effects that contributed directly on runoff, sediment concentration and soil loss increase: 1- bare or exposed soil where litter was removed and where splash, rill and interrill erosion could act more easily. 2- The unstable riser exposure became a good source of soil particles for soil loss. This steep riser component could even have small slides due to workers walking through the coffee plantation. 3-The disturbed superficial soil material was deposited in downhill position where it can be easily transported out of runoff plot. On the other hand, the NT treatment (no mini terraces renewal) showed high runoff production as rainfall increased together with slightly higher sediment concentration but not as much as renewed terraces. A recommendation from our experience about this practice of mini terraces renewal would be to prepare them in a time with low rainfall incidence and not just before rainy season peak (October). The mini terraces renewal need time to stabilize, and a good time would be beginning rainy season or just after it ends (end of November).

The reduced pruning had a positive effect on runoff reduction due to two main changes: 1. soil coverage increase and obstacles for runoff movement, and 2. canopy coverage increase that helped in raindrop impact reduction and at the same time increased interception of rainfall thus less runoff production.

In terms of soil coverage, visual evaluation was fast and consistent and therefore could be used for other studies as an alternative method to track coverage changes in big areas that need to be covered fast. A more detailed study on shade trees contribution on litter under steep lands is suggested.

In addition to our three periods of monitoring: (i) a stable period prior treatments application, (ii) a transition period and (iii) a year after, more data from the following years (2014-2015) could help to understand better the process and confirm the observed trends.

Chapter 4. Runoff and soil loss from plot to watershed scale under steep soil with coffee cultivation and tropical conditions, Costa Rica

Abstract

The aim of this work was to measure and analyze soil erosion processes in a shade coffee system on steep land at two spatial scales: plot and watershed. The plot scale corresponded to 137-358 m^2 (60-70% average slope) and the watershed scale was 31 ha approximately with 50-60% average slopes. It is known that erosion processes do not evolve the same way at both scales, but it is not common to have a watershed covered mostly by a single crop, the same used in the plots. The main dependent variables were superficial runoff and average sediment concentration. Rainfall data and dependent variables were collected from July 2012 until November 2013; where 2012 was very dry (28% below average) while 2013 was close to rainfall historical average but very low soil water content still affected by previous dry year. The runoff increase as the annual rainfall increase did not occur at both scales, only the watershed followed that trend. The watershed runoff increased from 12.7 mm to 21.8 mm in 2012 and 2013 respectively. The plots runoff decreased from 35.2 mm to 23.3 mm in 2012 and 2013. The mini-terraces renewal in six out of eight plots in 2012 seems to be the reason of this runoff dropping. The sediment concentration in plots was very stable with few peaks (between rainfall events), but when it was measured during a watershed discharge, the dynamic in sediment concentration showed this variable moved from very low concentrations up to 9 g l^{-1} or even higher (captured by a turbidimeter reading every 10 min). Base on sediment concentration peaks and watershed runoff peaks, the onset of rainy season had sediment concentration at flume coming from stream flow mostly and at the end of that rainy season, sediments came from other areas in the watershed. Following the same trend as runoff, the estimated annual soil loss was 0.46 and 1.24 t ha^{-1} yr^{-1} at watershed scale for 2012 and 2013 respectively and 0.73 and 0.36 t ha^{-1} yr^{-1} at plots scale for same years. The drop in soil loss at plot scale in 2013 seemed to be related with mini-terraces renewal that increased runoff just after they were rectified, but reduced runoff a year after they were more stabilized in coverage and unstable risers. Annual runoff coefficient at both scales was very low, also when rainfall increased in 2012. The runoff coefficients were 0.9% in both years at watershed scale. It was 2.44% and 0.9% in 2012 and 2013 respectively in plots. This means a good infiltration capacity reflected at both scales where coffee crop predominates. The watershed baseflow was also very low in this watershed (13% and 16% of total rainfall in 2012 and 2013 respectively); interception and evapotranspiration were estimated (not measured) between 10-13% and 45-53% of annual rainfall; change in soil water storage first 150 cm depth was negative: -120 mm and -1.5 mm in 2012 and

2013; and the remaining part of rainfall percolated representing between 20-40 % of annual rainfall.

Keywords: *steep slope, soil erosion, sediment concentration, runoff, watershed, scale*

4.1. Introduction

The whole soil erosion process (detachment, transport and deposition) is scale dependent, for example, sediment deposition is likely to be much more present at watershed scale than it would within a small plot area (< 10 m^{-2}). The consequence is that measured soil erosion rate generally varies from small plots to large scales (watersheds) under similar weather conditions (Cerdan et al., 2004; De Vente et al., 2007) even with homogeneous land use. There are many factors affecting these changes with scale such as spatial variability of lithology (Descroix et al., 2001), land use (Le Bissonnais et al., 1998; Valentin et al. 2008), soil surface coverage (Descheemaeker et al. 2006; Blanco y Aguilar 2015), hydraulic conductivity (Descroix et al., 2002; Verbist et al., 2010), or infiltration changes under different slopes (Zhu and Zhu, 2014). We may also have emergent features or processes at larger scale such as large exchange of surface water between catchments (Chappell et al., 2004), overland flow pattern, natural and human pathways (Ziegler and Giambelluca, 1997; Cerdan et al., 2004), rill or gully erosion (Chaplot et al., 2005), landslides and river banks erosion (Verbist et al., 2010).

The rainfall characteristics could vary spatially in a watershed and could also explain a large part of the sediment export variability (Descroix et al., 2001). Many studies did not have the chance to monitor rainfall variability across the watershed due to relying on only one weather station close to the study site. In fact, it would be fair enough to expect the larger the study area, the larger the spatial variability in rainfall distribution.

These various types of spatial variability effects should be taken into account when up-scaling erosion rate assessment from plot to watershed areas is attempted.

The up-scaling can be relevant when the extended area is relatively homogenous and similar to plots soil. However, De Vente and Poesen (2005) warned that results from one scale should not be considered representative for other scale. Processes as sheet, rill, gully and bank erosion vary depending of area. For example, watershed greater than 5 ha approximately have more gully erosion affection than smaller areas (Poesen et al., 1996). Roads, channels and human pathways usually are not present at plot scale and their effects are only observed at watershed scale (Ziegler and Giambelluca 1997; Rijsdijk et al. 2007, Verbist et al., 2010; Collins et al., 2012). Gómez-Delgado et al. (2010) found roads that covered 4.5% (represented as 10 km road length) of a 0.9 km^2 watershed as one of the main sources of runoff. Ziegler et al. (2004) measured 80% of road runoff that could become a good source of high flow runoff into plantations.

Sediment yield at plot and watershed scale measurements could differ in both directions due to spatial and temporal variability in a watershed (Huang et al., 2001; De Vente et al., 2007; Duvert et al., 2010). Descroix et al. (2002) measured from three similar and close each other watershed in Mexico sediment yields from 0.3 t ha^{-1} y^{-1} up to 15 t ha^{-1} y^{-1} which demonstrated the high variability of sediment yield in relation with the scale of measurement.

Soil loss from permanent crops systems under steep lands such as coffee under agroforestry system has been reported at plot scale, but not at both scales at the same time. This is a contribution that this research offers to the cumulated knowledge in soil erosion under shade coffee and steep slopes.

The main objective of this investigation was to compare surface runoff and erosion rates measured at coffee plots and watershed scales. This comparison should allow explaining the main mechanisms of runoff and sediment production and flux at the outlet of the watershed and thus helping to determine the most efficient management options to reduce runoff and erosion.

4.2. Material and methods

4.2.1 Watershed characteristics and land use

The experimental watershed (refers to WS from now) covered *ca.* 31 ha (Fig. 4.1), 0.35 km at its maximum width and 1.30 km long (from outlet at 1493 m.a.s.l. to farther top watershed border at 1780 m.a.s.l). The stream sourced at 1675 m.a.s.l. and was approximately 1.05 km long, with an average slope of 19%. The geographic coordinates (WSG 1984) in the middle of the watershed are approximately 9.674453° N and 84.092423° E.

The watershed is almost 85% covered by coffee plantation under the shade of *Erythrina sp* (mostly) and banana (*Musa spp.).* The average soil slope under coffee is between 50-60 %. Table 4.1 summarizes other land covers such as sugarcane, riparian forest and gullies spots to the West side of the watershed. The total roads length is around 4.3 km representing approximately 5.6% of the total watershed area: 2.2 km under gravel road, that is, bare soil cover by crashed stones in order to improve small truck traction specially in rainy season; and 2.1 km as dirt road (bare soil with no crashed stones addition). There is only one small house (close to the weather station) used as stowage which area was considered insignificant as compared to the watershed area.

Table 4.2 shows a general agenda of the main activities made in the plots and in the watershed. At watershed scale, two farmers (Ramiro Garro and Rafael Prado) own around 90% of the total watershed area. Ramiro Garro owns most of the Eastern part of the watershed and Rafael Prado owns the Western part. Two small coffee areas (5% of the total area approximately each), owned by two different farmers, followed a management schedule similar as the one followed by Rafael Prado. This means that basically there were two types of managements in the watershed covering 50% of coffee area each approximately. Both managements included coffee pruned every year at similar time (March), as did also the owner of the runoff plots. The pruned coffee branches were left on the soil, perpendicular to slope direction. The coffee terraces on the West side of the watershed were renewed in 2011 while the renewal dated back to 2007 in the East.

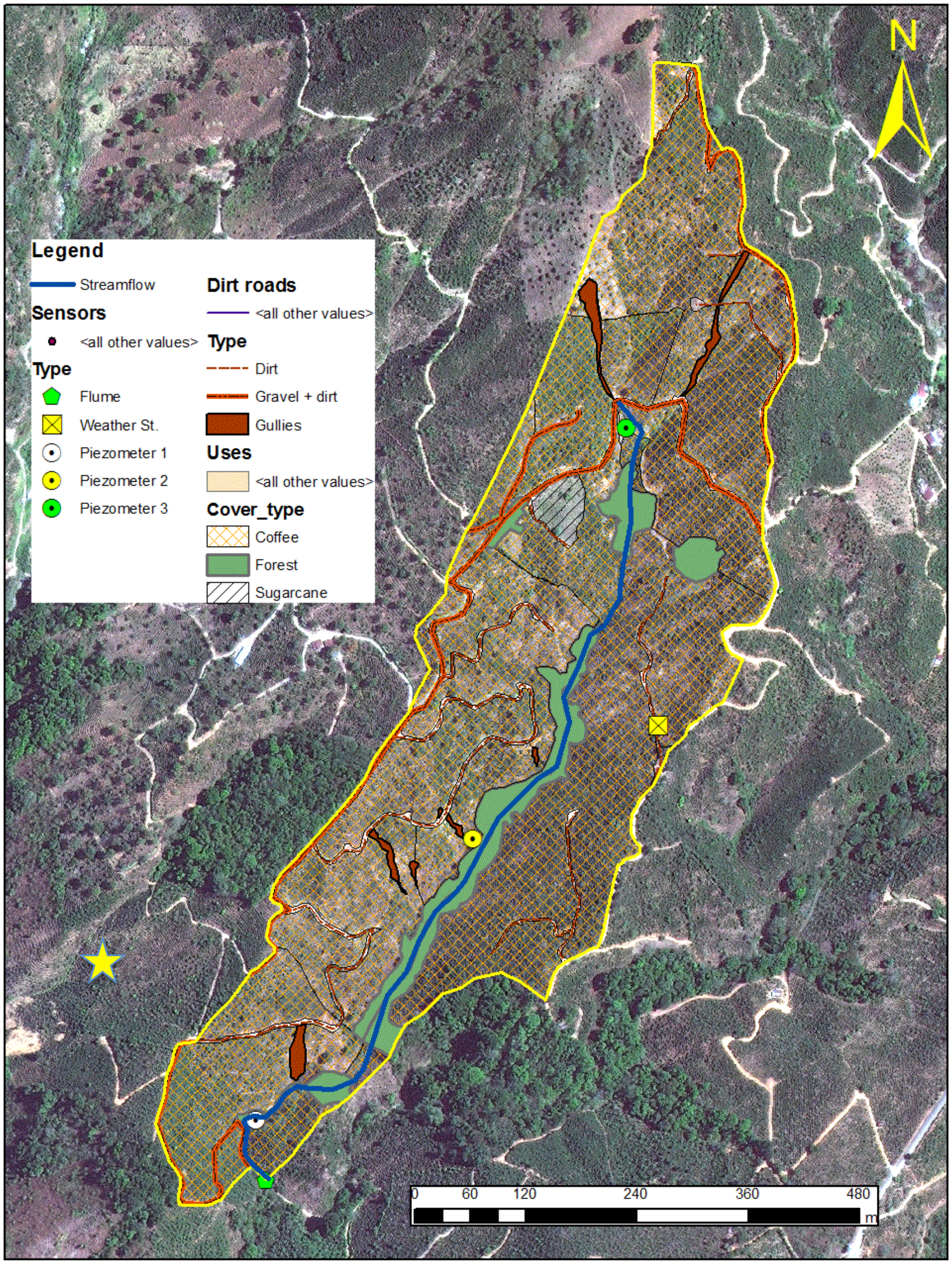

Figure 4.1. Garrito watershed (the yellow line marks watershed border), roads and land coverage type. The yellow star shows the location of the runoff plots. San Isidro, San Pablo de León Cortés.

Table 4.1. Area distribution by land use in Garrito watershed.

Coverage	area (m^2)	%
Coffee	263 049	84.85
Forest	22 808	7.36
Sugarcane	3 026	0.98
Gullies	3 601	1.16
Dirt roads	8 467	2.73
Gravel roads	9 049	2.92
TOTAL	310 000	100.00

Table 4.2. Coffee management agenda at experimental plots (specific dates given under month columns) and Garrito watershed (month the coffee owner proceeded) from 2011-2013. San Isidro, San Pablo de León Cortés.

Practice	Year	Place	April	May	June	July	Aug.	Sept.#	Oct.	Nov.
Mechanical weed control	***2011***	Plot			30		29	12-14		
		WS			▦			▦		
	2012	Plot			15-23*		23-27			21-23
		WS			▦					
	2013	Plot			26-27			18-25		
		WS			▦			▦		
Shade pruning	***2011***	Plot				16-20			25-31	7-8
		WS	▤				▥			▤
	2012	Plot	30	1-2				13	3-5	▤
		WS	▤				▥			
	2013	Plot		14-19				30	1-4	
		WS	▤				▥			▤
Herbicide application	***2011***	Plot						14, P	13-14	▤
		WS				▥				
	2012	Plot					1			20,
		WS				▥		▥		▤
	2013	Plot				17			1-7	
		WS				▥		▥		▤

* Mechanical weed control was done also on herbicide plots. No herbicide treatment effect yet.

Terraces were renewed in six out of eight plots (days: 18, 19, 20 & 25)

▤ It means Ramiro Garro did the practice, West part of watershed.
▥ It means Rafael Prado did the practice, East part of watershed.
▦ It means Ramiro and Rafael did the practice.

4.2.2 Monitoring and measurements

The watershed total flow and sediment suspension at the outlet was monitored by a 3 $m^3 s^{-1}$ capacity long-throated steel flume (Fig. 4.2) installed at 0.048 gradient and the stream flow average gradient in the installation site was 0.06. The flume dimensions were 3.9 m, 2.8 m and 1.2 m length, width and height respectively. This flume was built in cooperation with ICE (Instituto Costarricense de Electricidad) workshop.

Fig. 4.1 has the location of equipment installed in the watershed. Two weather stations (HOBO) measured rainfall (mm), temperature (Celsius), radiance (uE) and wind speed (m s^{-1}) every 10 min. There is around 500 m distance from one weather station to the other (watershed and runoff plots). Three piezometers were installed along the watershed close to the main stream. Flume and weather station data were taken from July 2012 to November 2013 and piezometer data were recorded from February to December 2013. During the dry season (December to April) the flume sensors were disconnected due to very low stream flow (< 10 l s^{-1}) that was not detected by transducer and the turbidimeter sensors.

Eight erosion plots were located SW of the watershed (outside). Runoff, soil moisture and rainfall were measured automatically every 5 min. Sediment samples were taken after each rainfall event. The same treatments mentioned in chapter 2 were continued.

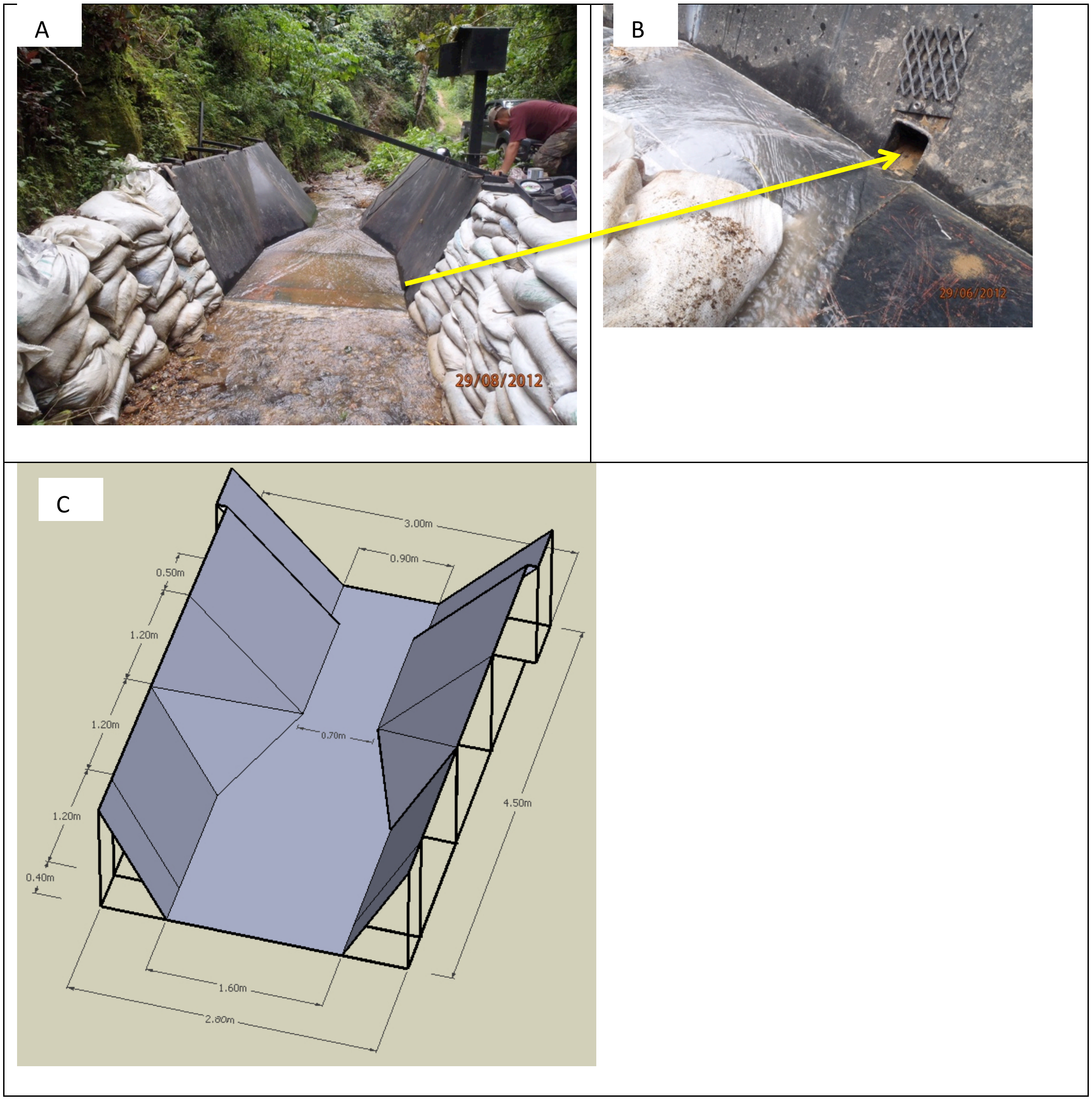

Figure 4.2. Flume installation, dimensions and sensor tunnel location. **A:** Flume (3 m^3 s^{-1} capacity) installed in Garrito watershed outlet since July 2012. **B:** flume-monitoring tunnel where sensors (turbidimeter and transducer) were installed. **C:** Flume dimensions installed at Garritos watershed outlet; up side corresponds to tail.

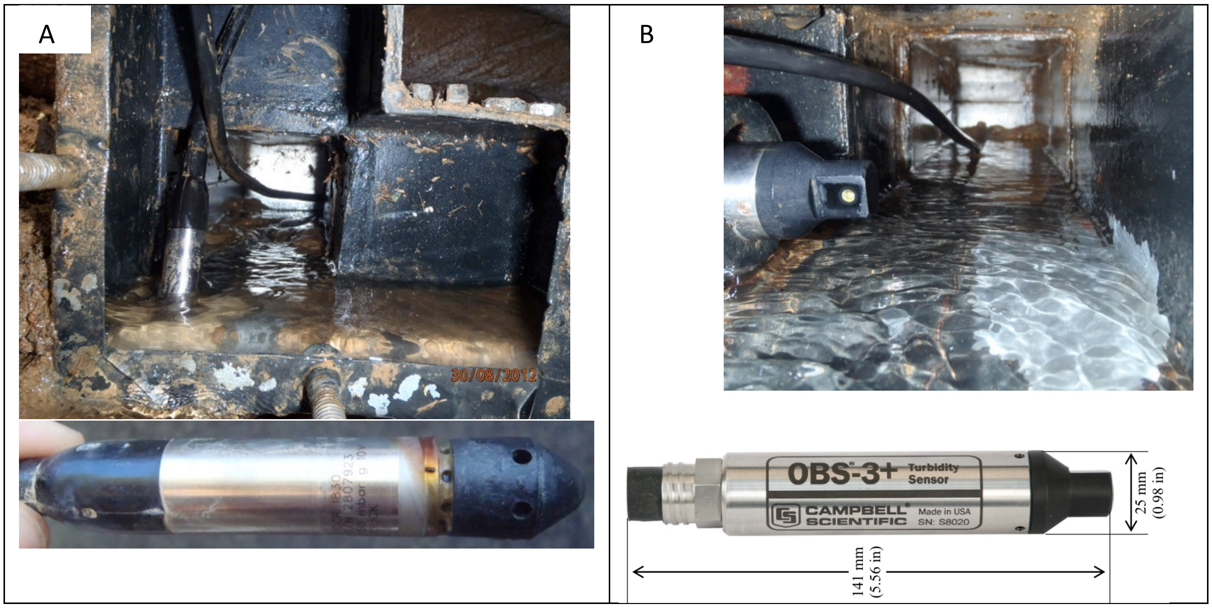

Figure 4.3. Sensors that monitored water column and sediment suspension. **A:** General Electric pressure transducer installed at the back of flume monitoring tunnel. **B:** Campell Scientific OBS-3+ turbidimeter installed in the entrance of flume monitoring tunnel.

4.2.2.1 Sensor description and calibration

The water level in the flume was measured by a PDCR 1830 transducer sensor (General Electric). The sediment concentration (expressed in grams per liter) was measured by a turbidimeter (OBS-3+; Campbell Scientific) by an optical backscatter sensor or turbidity sensor pointed to the stream. The turbidity measured in FTU (Formazin Turbidity Units) with accuracy of 2%. Both sensors were factory calibrated, but new calibrations were performed following factory recommendation using sediments from same sampling site.

Pressure transducer calibration came from 56 measurements got in the field from 2012 and 2013. Low flume levels (<10 $l\ s^{-1}$) with high variation in pressure transducer records had to be discarded since water column height (< 0.5 cm) was out of sensor sensibility. However, extreme events become more reliable and convenient for runoff and sediment suspension (1200 FTU equivalent to 9 $g\ l^{-1}$ approximately) analysis at watershed scale.

The estimated water level at flume base on transducer readings was done by a calibration. This calibration function was built from artificial water columns using a bucket with water (prior installation into the flume) and field measurements in real time once installed in the flume (Fig. 4.4). After this estimated water level was determined, the water flow (Q, $m^3\ s^{-1}$) was projected by a rating curve (Fig. 4.5). This rating curve was estimated by Winflume software (Wahl et al., 2000) considering geometric and hydraulic flume properties.

The turbidimeter calibration function was obtained from 23 flume water samples (470 ml) at different discharges. They were taken to the laboratory (ICE) and total sediments from sample were separated by filtration, then dried up in oven at 104º for 48 h and then weighted. The turbidimeter cannot measure sediment suspension beyond 1200 FTU (equivalent to 9 g l^{-1} approximately) values thus a sub-estimation in sediment yield was likely under high discharges with high FTU readings above 1200 FTU.

All measurements in the flume were recorded in a CR1000 datalogger (Campbell) every 10 min.

Three piezometric wells were made at 2.97, 2.03 and 4.18 m depths for piezometers 1, 2 and 3 respectively (Fig. 4.1). Each well was drill by a 5 m long detachable auger and 2.5” width. Then a one-piece PVC 2” tube was cut and at the extreme of the tube several perpendicular perforations were made with a hacksaw over a 30 cm long from tube base. In order to avoid silt and clay entrance to the tube perforations a hand made tight sock of low permeability material was installed and retained by plastic strips. Each piezometer was monitored by pressure transducers (MicroDIVER DI 601-10m; accuracy ± 1 cm H_2O and resolution ± 0.2 cm H_2O; Schlumberger Water Services Technology) and one atmospheric pressure sensor (BaroDIVER) located in piezometer #2 in the middle of the Watershed. The atmospheric pressure was used to correct automatically by Diver software the water head values for the variations of atmospheric pressure. All automatic measurements were every 10 min since January 2013 and downloaded using a PC (USB) DIVER adapter.

Piezometer data from three sensors were checked using equation (4.1), which compares variability of each sensor against other two and if they behave similar, and then one could assume same monitored aquifer.

$$Pvar_i = \frac{(Pi-Pa)}{P\_SD} \qquad (4.1)$$

Where *Pvar*$_i$ refers to piezometer reading variability point in time lap “i"; Pi is piezometer reading at given time; Pa is piezometer reading average for whole period of measurements (April to Dec. 2013) and P_SD is standard deviation for complete piezometer readings period.

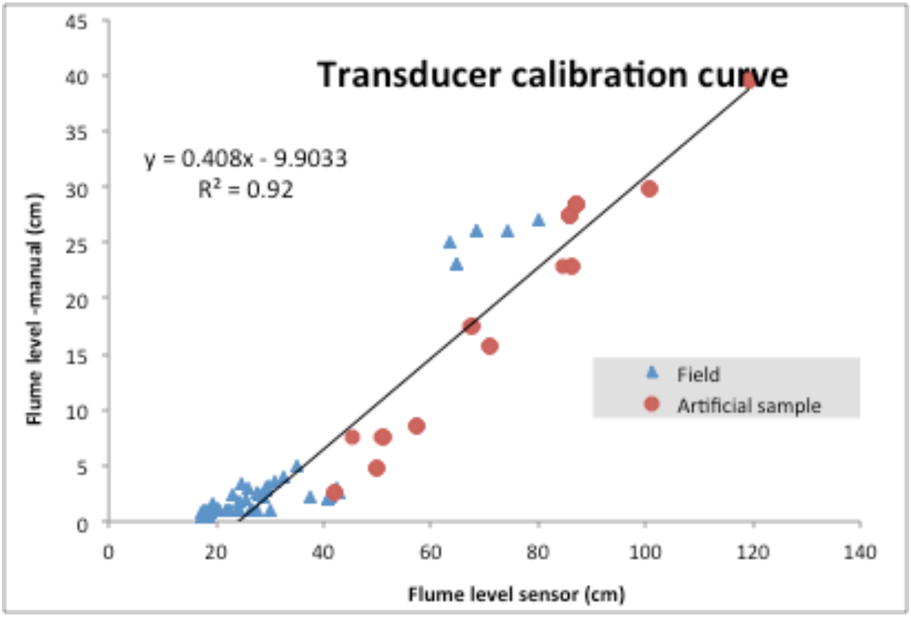

Figure 4.4. Calibration curve for flume transducer (PDCR 1830 GE). Rounded points correspond to measurements in a container prior flume installation. Triangular points correspond to measurements from in situ water level at flume after transducer installation.

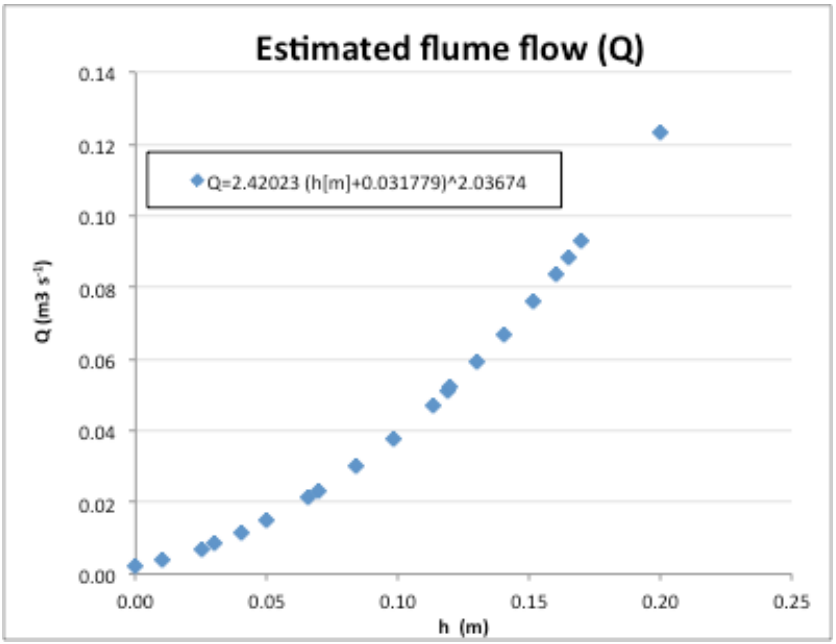

Figure 4.5. Calibration for continues flow curve for a 3 m^3 s^{-1} maximum capacity flume based on water flow column height. The theoretical curve was estimated by Winflume software according to flume dimensions and gradients installation.

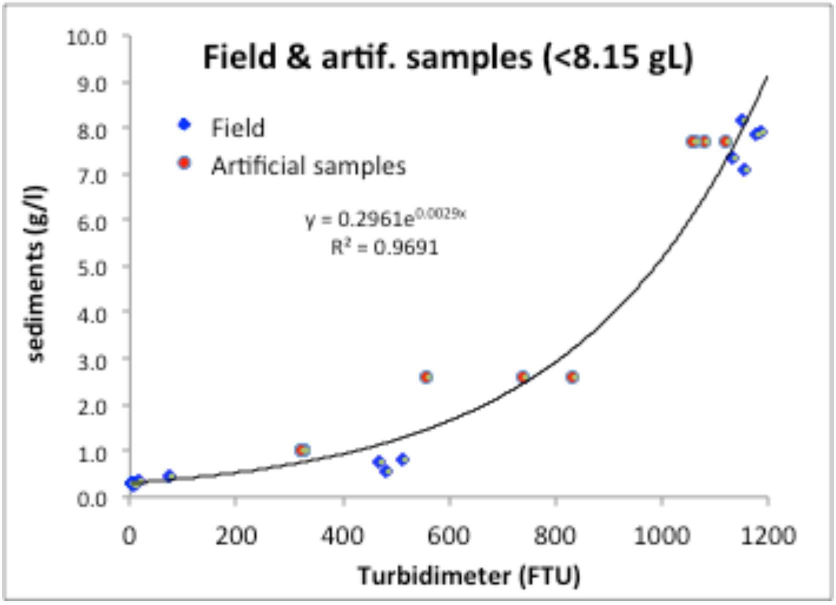

Figure 4.6. Calibration curve for turbidimeter (OBS-3+ Campbell Sc.) up to 1200 FTU. Values over and close to 1200 FTU could correspond to sediment concentration > 9 g l^{-1}.

4.2.3 Data approach, downscaling

Monthly rainfall from both weather stations was summarized monthly and separately. A rainfall event was considered as one by following the same criteria used in chapter 2.

The watershed data of continues flow (Q_b: baseflow) and flow increases (denoted as Ro_WS: watershed runoff due to rainfall events) were integrated to rainfall scale. Also sediment concentration and total soil loss was integrated at rainfall event, which allowed comparison between watershed and plots in real time events.

A summary of piezometer data was used for checking soil water table variation due to rainfall-runoff dynamic besides a general annual water budget at both scales.

Cumulative data for watershed runoff, rainfall and baseflow were estimated and used for rainy periods comparison.

Runoff, sediment concentration and soil loss are compared for all rainfall events above the determined rainfall threshold where runoff is produced at both scales,

Finally, a comparison between the two scales was made looking for any difference in runoff production, sediment concentration (only for watershed data since plot sediment concentration was sampled after rainfall event) and soil loss under same rainfall events allowing a deeper analysis into specific rainfall events (high depths events) at beginning, middle and end of rainy seasons but mostly for 2013 due to low data availability from a dry 2012 year.

4.2.3.1 Watershed runoff, sediment concentration and soil loss

Watershed runoff (Ro-WS) was estimated from increases in water level at flume (registered by transducer sensor) with respect to baseflow (Q_b) prior the rainfall event. Over the same rainfall events, the readings from the turbidimeter were transformed to sediment concentration (SC; in grams per liter unit). From these records two different mean SC can be estimated:

1- The average SC^{WS} for a rainfall event calculated as the average sediment concentration of all 10 min lap records independently of total flux per rainfall event. This record is useful for dynamic of sediment concentration over a rainfall.
2- The SC weighted estimation (SCw) from flume measurements calculated by applying equation (4.2). This value is the one that can be compared with plots average sediment concentration.

$$SC_W = \frac{\sum_i^n (gL_i^{wS} * QT_i)}{\sum_i^n QT_i} \qquad (4.2)$$

Where SCw represents average weighted sediment suspension (10 min time lap) at watershed flume point in g l^{-1}, QT is the total flow volume (liters) estimated at 10 min lap from first 10 min a rainfall was recorded up to “n” intervals until rainfall ended. The SCw is used for comparison between plots and watershed average sediment concentrations. This is required since sediment concentration from plots corresponds to a runoff sample collected after rainfall event that was measured after rainfall events and total runoff volume was relevant diluting sediment concentration.

The total soil loss from watershed was estimated by the summation of total water volume (QT) every 10 min multiplied by the respective 10 min average sediment concentration (SC^{WS}). Meanwhile, the soil loss from plots is the multiplication of average sediment concentration by total runoff registered by corresponding rainfall event.

4.2.3.2 Watershed vs Plots

In order to match rainfall events at plot scale with watershed rainfall, all rainfall events (in the watershed and plots site) were identified with the same code. In case an event was not present or registered in the counterpart weather station (i.e. only watershed but not in the plots or vice versa) then intermediate event identification was created and that event was not used for comparison. This allows comparing only similar events in time.

Runoff comparison between two scales was also analyzed by splitting rainfall events on different depth categories. Rainfall events below 5 mm depth had low contribution to runoff production (experience from chapter 1: Descheemaeker et al. (2006) observed rainfall threshold for runoff production over 3mm) and rainfall events over 40 mm depth had an important runoff production, thus a category for this group. Four rainfall depth categories were selected: < 5 mm, 5-20 mm, 20-40 mm and > 40 mm.

4.2.3.2.1 High rainfall-runoff events

From all rainfall events registered, only events that produced runoff could show a complete dynamics in runoff production and sediment not just at watershed scale but also at plots scale. These specific events could show dynamic differences between both scales. They were chosen based on rainy season time, at least one specific event at the beginning, the middle and end of this season. The dynamic in rainfall, superficial runoff over a rainfall event was analyzed at both scale, and sediment concentration changes at watershed scale only. Possible explanations could be related to coffee plantation management (Plots and WS), roads, gullies, topography and rainfall heterogeneity.

4.2.3.3 Water balance budget: Plots and watershed

An annual hydrology balance at plot and watershed scales could lead to distinguish percolated water where runoff difference (between both scales) determines it since evapotranspiration (ET) and interception (Int) were the same under both scales.

Interception was estimated as Siles et al. (2010) suggested separating rainfall event by depth categories and assuming a fix percentage of interception per category. In term of rainfall, total water income to the system was expected to be similar; therefore the rainfall average between both weather stations was used.

Under coffee systems, there are studies with different estimation of coffee transpiration. Gómez-Delgado et al. (2011) measured 818 mm of evapotranspiration (ET) at Aquiares coffee plantation under *Erythrina sp.* shade trees (Humid Tropical forest) in 2009, Turrialba; van Kanten and Vaast (2006) measured 897 mm of transpiration in Southern Costa Rica for a year; Siles (2007) got 1310 mm and 1178 mm of ET in San Pedro de Barva (Heredia) for two consecutive years; Imbach (1989) measured 915 mm of ET under coffee shaded with *Erythrina spp.* experiment site in Turrialba; and Jiménez (1986) measured 750 mm (almost 7 months period) under shade coffee system in Turrialba which if linear extrapolation is assumed it corresponds to 1285 mm. The linear extrapolation is not precise since evapotranspiration is not continuous and varies based on weather and plant type but gives some clue where the value could be. In terms of plant coverage, Shuttleworth and Wallace (1985) affirm that ET is 100% from plant if LAI > 3 and soil is not saturated at its surface. LAI measured (monthly) in the same runoff plots site in 2012 from Meylan (2013) were between 4.34 (January) and 6.28 (November) thus ET could be assumed from coffee mostly. Even more, both studied years were dry years and soil saturation was reached only few moments and for short periods (<1 h).

The general water balance applied was:

$$P = Ro + ET + Int. + Perc. + \Delta\ SWC + error \qquad (4.3)$$

Where P is precipitation in mm; Ro is superficial runoff; ET is evapotranspiration; Int. is interception; SWC is soil water content and error represents any systematic or instrumental uncertainty.

The change in soil water content (SWC) was calculated base on the first 150 cm of soil profile depth from TDRs records as the volumetric water difference (in mm) between beginning and the end of the period in study.

4.3. Results

4.3.1 Rainfall

There were 330 rainfall events for the study period (July 2012-Dec. 2013) where 2 of them occurred at watershed only. Basically there was no runoff (very low or absent in most of the plots) under rainfall events below the 5 mm depth. However for general analysis purpose in this chapter these 161 small events (<5 mm) in terms of rainfalls depth were also considered, but not for deep rainfall-runoff dynamic analysis.

The annual rainfall in 2012 (Table 4.3) was very low compared to 1990-2006 annual average (2460 ± 407 mm; Carrizales weather station) whereas annual rainfall in 2013 was around average. The difference of 448 mm between both rainy seasons (plots weather station data) is a large amount of water (approx. 28% of average annual rainfall). Table 4.3 also shows the differences observed between rainfalls at watershed and just next to the watershed, in runoff plots location. The largest monthly rainfall differences in 2013 were in May and September (46 mm and 42 mm) and the other months rainfall were closer, however at rainfall event some of them were important in terms of rainfall depth and time.

Table 4.3. Summary of total rainfall (mm) from the two weather stations (Plots and watershed) for 2012-2013 rainy seasons. San Isidro de León Cortés. Costa Rica

Weather station	Year / Month	May	June	July	Aug.	Sept.	Oct.	Nov.	Rainy season
WS	**2012**	-	-	-	-	-	371[#]	73	-
Plots		263	221	208	411	290	315	72	1780
WS	**2013**	316	355	176	283	539	523	141	2333
Plots		270	348	165	297	497	509	142	2228

#: The weather station was installed in the watershed on October 17th 2012, thus total rainfall in the watershed is a combination of data of both weather stations.

4.3.2 Watershed outlet runoff and erosion results: seasonal scale

4.3.2.1 Runoff

The 161 rainfall events below 5 mm depth each had a very small contribution to total superficial runoff (0.9% and 2.4% for plots and watershed respectively). At watershed level, those events contributed 0.83 mm out of 34.5 mm total runoff and at plots scale level those rainfall events produced 0.21 mm out of 58.5 mm (July 2012-Dec. 2013 period) total runoff.

In 2012 watershed response in terms of superficial runoff (Fig. 4.7 A) was low compare with data from 2013 (Fig. 4.7 B) where runoff discharges were higher comparing as a whole, but the contrary when reported as a percentage of total rainfall. Fig. 4.8 shows how QT and baseflow (Q_b) increased in 2013 compared with 2012 baseflow thus watershed runoff increase in 2013 was smaller than expected when compared proportional to total rainfall.

The cumulative rainfall and watershed fluxes (QT, Qb and Ro_WS) allow determining in a different way any response to rainfall discharges throughout the rainy seasons. Fig. 4.8 shows how runoff response (steeper lines) was stronger to rainfall at watershed in 2013 than 2012. However, by comparing Ro_WS in both years it was quite low (17 mm in 2012 –July-Dec. period and 21.8 mm for 2013). Furthermore, annual runoff coefficient was low for both periods (almost 1%).

The water baseflow was a large component of total watershed stream flow (93 and 94% for 2012 and 2013 respectively), however it is a small outflow component of total water input to the watershed (12.9 and 16.2% of total rainfall). Gómez et al. (2011) measured a baseflow that represented 56% of total rainfall under a deep volcanic soil (Andosol) with large infiltration capacity in a 90 ha watershed. Nevertheless, Charlier et al. (2008) under 18 ha watershed with volcanic soils in Guadaloupe island measured 17% of total rainfall as baseflow. Also Kinner and Stallard (2004) in a 10 ha watershed in Panama measured 20% of total rainfall as baseflow. Although these values could differ because different total rainfall conditions and evapotranspiration according to main coverage, our results seem to be close to other watersheds.

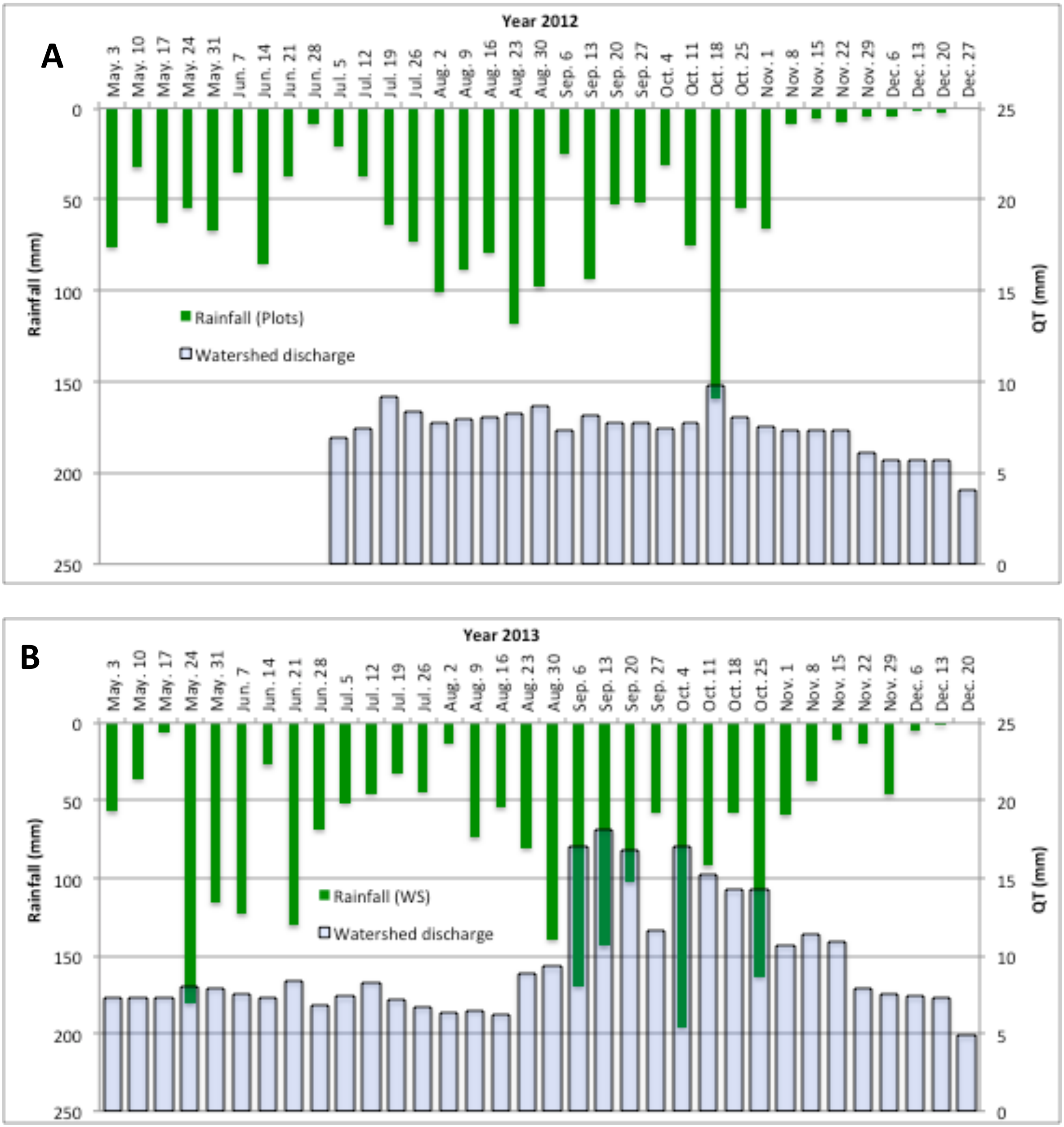

Figure 4.7. Watershed continuous weekly discharge registered at flume checkpoint and rainfall. **A**: Rainfall at plots and partial WS discharge (flume data from July 7th). **B**: Rainfall at WS and WS discharge 2013.

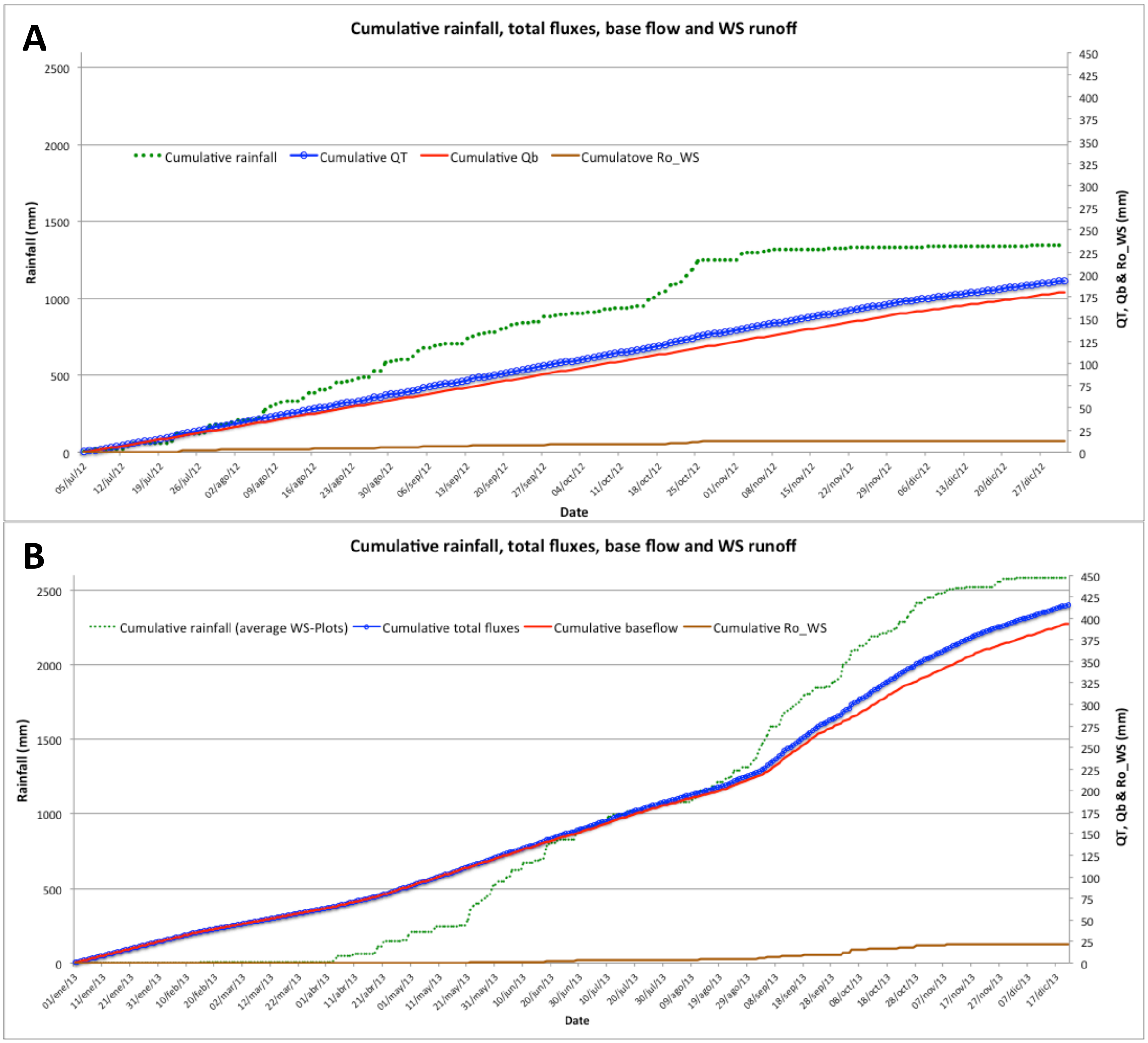

Figure 4.8. Cumulative watershed runoff, total discharge (Q total), baseflow (Qb) and rainfall (Rf) registered at watershed outlet from July 1st 2012 to November 2013.

4.3.2.2 Sediment concentration and erosion

Sediment concentration was relatively stable (Fig. 4.9A) under rainfall events in 2012 with daily average values around 0.40 g l^{-1} (SC^{WS}). A similar trend on sediment concentration was present onset of rainy season 2013, however after September 2013 sediment concentration increases were higher and showed a more dynamic response to rainfall events. The low daily average sediment concentration in July and August 2013 was related with a decrease in rainfall events (temporal dry season that usually last 2 weeks extended almost two months). Rainfall depth per event and sediment concentration correlations (SC^{WS} and SCW) was 67 and 70% respectively, which was not the case for plot scale (Chapter 2) with 9% correlation.

At watershed scale (Table 4.5) soil loss was low in both years but total amount increased almost three times in 2013. Soil loss from 2012 is from half year, but it is the period where more than 70% of the annual soil loss was observed at plot scale (Chapter 2) and in 2013 was 86% of annual soil loss at watershed, thus higher soil loss if whole 2012 would be monitored by flume should not be much different. This low erosion rates were related to low runoff and low suspended sediment measurements, which could be under-estimated under high rainfall events that were scarce in 2012.

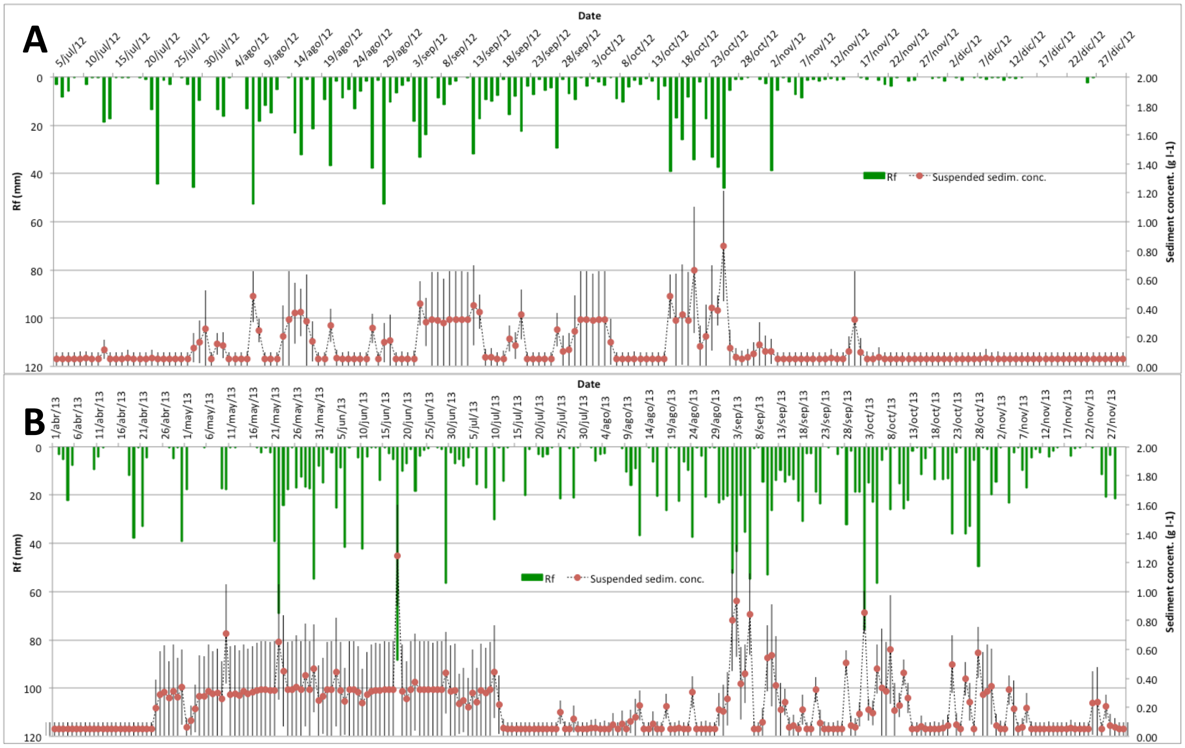

Figure 4.9. Daily sediment concentration (SC^{WS}) at flume point in 2012 and 2013 and rainfall depth. Vertical bars represent +- standard deviation.

4.3.2.3 Piezometers

Piezometer data show a high variability over dry season moving forward to more homogeneous changes under wet soil conditions. There were negative readings (dry dwells) from sensors until April 2013 that causes confusion on trend. A negative lecture could mean the water table moved below the sensor position, then the track was lost. Due to this condition records from May to December were used.

Piezometers data variability increased at the beginning and at the end of rainy season. Piezometers 1 and 3 varied similarly when values coming from equation (4.1) are used (Fig. 4.10A) in magnitude and dynamics whereas piezometer in position 2 (middle of WS) had smaller changes compared with others two which could mean a different aquifer than piezometer 1 and 3. Movements of water table were consistent to rainfall high events and dry periods especially under piezometer 1 and 3 (Fig. 4.10 B) reflecting a good infiltration dynamic in time response associated to low runoff pattern from watershed.

Fig. 4.10 B shows the movements of each piezometer sensor and it can be notice how the three water table were at different depths being the deepest on the top and outlet of the watershed (sensors 1 and 3). Sensor 2 presents a stable movement very low affected by rain pattern and water table relatively close to soil surface.

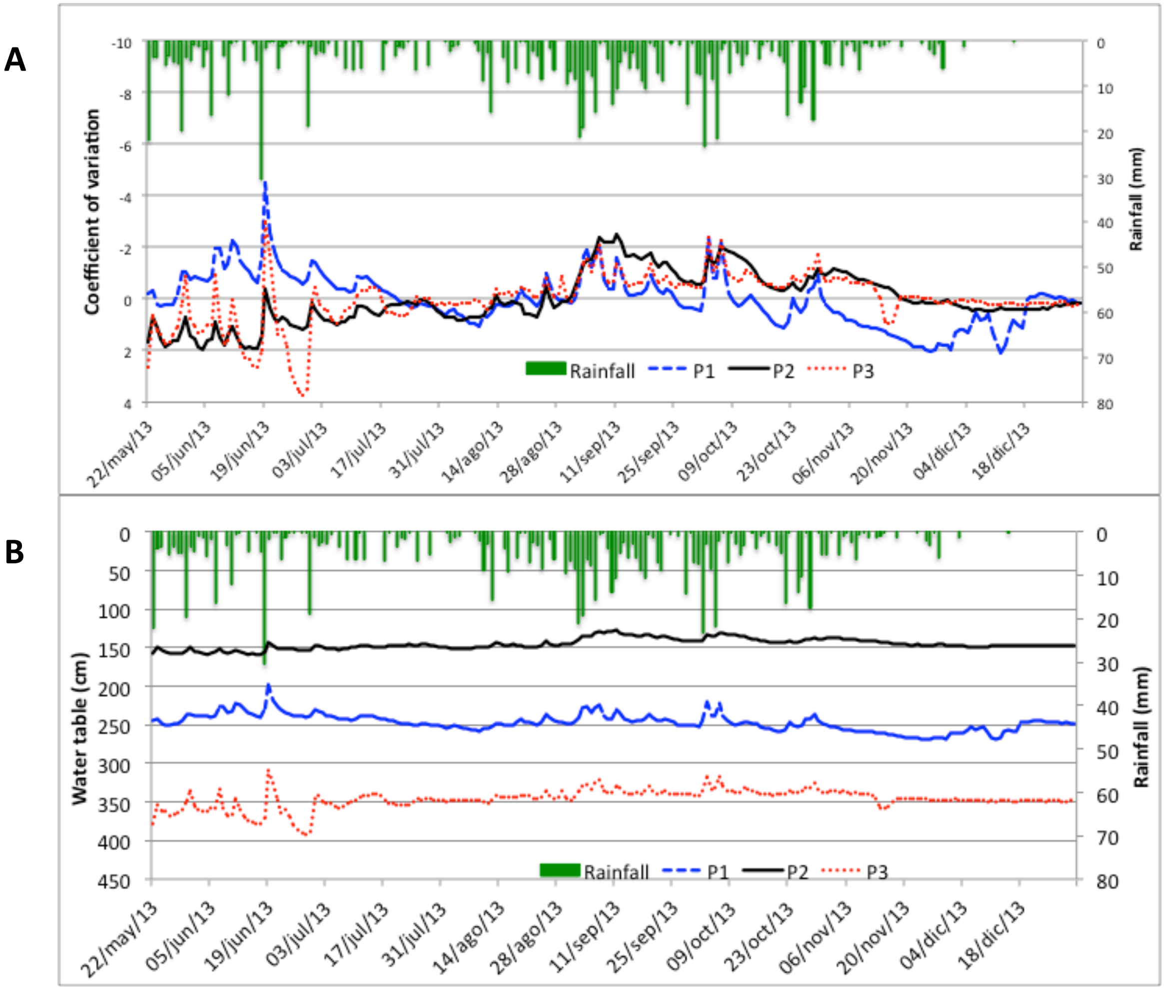

Figure 4.10. Daily piezometers registrations over 2013. **A:** Coefficient of variation applying eq. (4.1) for each piezometer record. **B:** Water table oscillation detected by the three piezometers throughout 2013, water table = 0 corresponds to soil surface level. Garrito watershed, San Isidro, San Pablo de León Cortés.

4.3.3 Comparison of Runoff and erosion WS vs Plots

Runoff, sediment concentration and soil loss are compared at both scales. The dynamic comparison is per rainfall event, daily and seasonal.

4.3.3.1 Seasonal trend comparison: runoff

The runoff at watershed level increased from 2012 to 2013, but the opposite was registered at plot level. From Table 4.4, watershed runoff increased around 72% and plots runoff decreased 34% approximately. Rainfall events below 5 mm depths had a very small contribution to annual runoff (< 2.7%) and soil loss in both years (data not shown). As it was described in chapter 2, rainfall events greater than 40 mm depth had a high contribution to annual runoff and soil loss and at watershed scale their relevance prevail. All rainfall events > 20 mm produced 79% of total runoff in the watershed in both years and around 85% of total runoff in the plots for both years too.

At event scale (Fig. 4.11A) the runoff measured from watershed was in general higher than runoff measured at plots scale at the beginning of rainy season. They moved closer each other as soil got wetter (Sept.-Oct.) and finally runoff from plots became higher than watershed. This increase in plots runoff in October also matches with the mini-terraces renewal. In 2013 (Fig. 4.11B) runoff rates were generally similar between watershed and plots but plots runoff overpass watershed runoff under high rainfall events (>40 mm) and wet soil condition (peak rainy season). Soil water measurements in plots could be a good proxy for watershed soil water content since is the same soil type and it is just adjacent to the watershed.

Coffee management influence on runoff production at watershed scale was not clear (Fig. 4.11). The coffee practices applied all over the watershed were not at the same time and due to the spatial extension, for example pruning took 2-3 weeks in one coffee farm. The soft rainy seasons in both years forced producer to change their practices, such as reduced herbicide application since weeds did not cover homogeneously.

Table 4.4. Superficial runoff summary at watershed and plot scale by rainfall depth category (330 rainfall events). July 2012-Dec. 2013. Garrito watershed, San Isidro, San Pablo de León Cortés.

Rainfall depth category	July-Dec. 2012					Jan.-Dec. 2013				
	n	WS	SD	Plots	SD	N	WS	SD	Plots	SD
< 5 mm	*79*	0.34	*0.31*	0.16	*0.14*	*84*	0.55	*0.75*	0.06	*0.10*
5-20 mm	*48*	2.33	*0.73*	5.20	*2.1*	*60*	3.92	*1.63*	2.87	*1.5*
20-40 mm	*15*	6.63	*0.94*	26.1	*13.3*	*30*	7.08	*2.13*	7.22	*4.0*
> 40 mm	*4*	3.41	*0.23*	3.81	*1.7*	*10*	10.3	*1.63*	13.2	*7.1*
All rainfall events	***146***	**12.7**	***2.21***	**35.4**	***17.3***	***184***	**21.8**	***6.14***	**23.3**	***12.7***

n: quantity of rainfall events
SD: Standard deviation

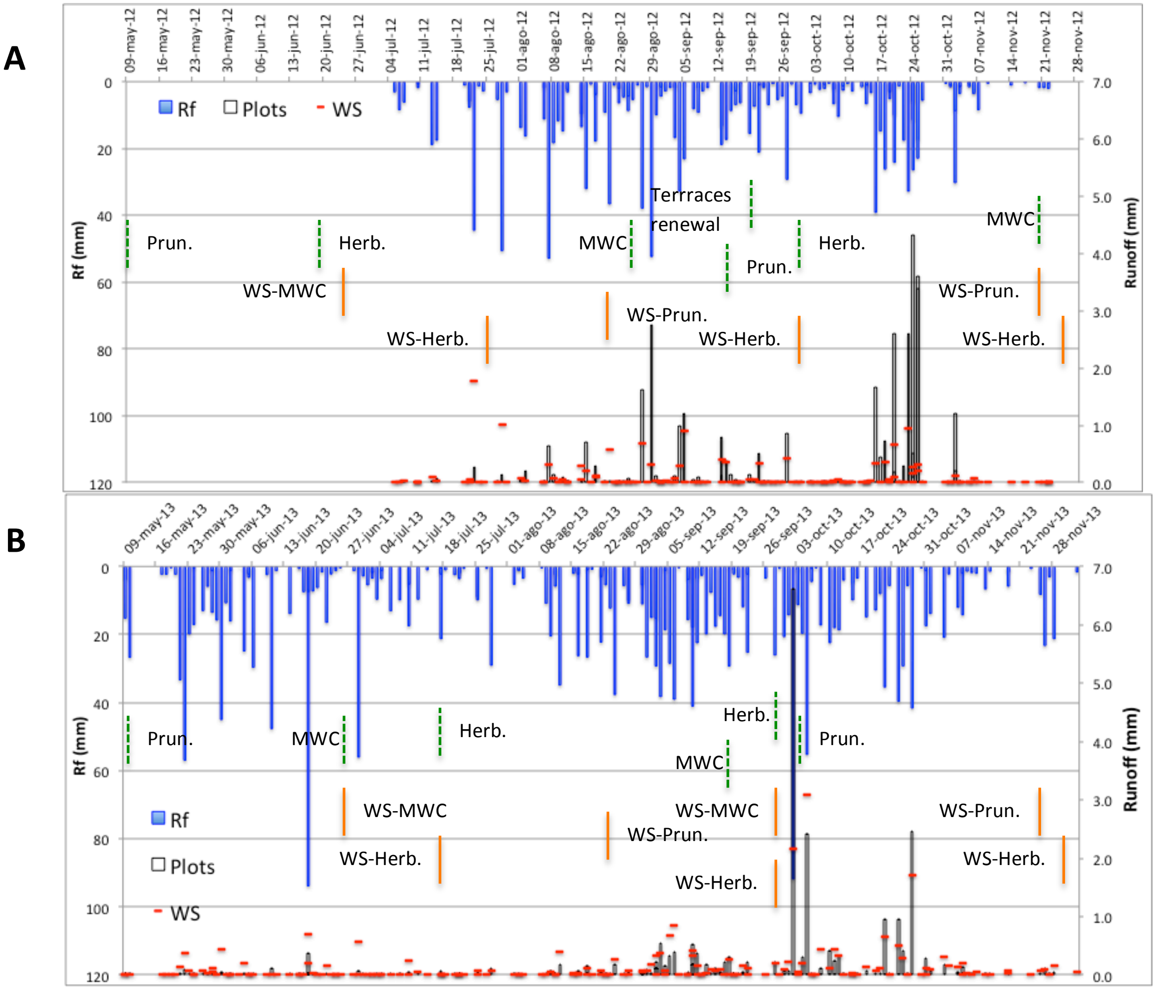

Figure 4.11. Total superficial runoff per rainfall event measured at plots scale (8 plots average) and watershed outlet (67 and 102 rainfall events > 5mm for 2012 and 2013 respectively). Vertical discontinuous green line indicates aprox. time coffee practice was made (Herb.: Herbicide application; Prun.: Pruning control; MWC: Mechanical weed control). Garrito watershed. San Isidro, San Pablo de León Cortés.

4.3.3.2 Seasonal trend comparison: sediment concentration and erosion

Sediment concentration was higher in 2012 (Fig. 4.12A) at plots scale than in the watershed (weighted sediment concentration; SC_W). However in 2013 (Fig. 4.12B) that difference decreased and watershed sediment concentration was higher more often (than in 2012) over the end of 2013 rainy season.

From Table 4.5, sediment concentration at watershed was always lower than plots sediment concentration. Even considering only average (weighted) sediment concentration under rainfall events larger than 5 mm, plots sediment concentration was still higher than watershed.

Total soil loss over 2012 rainy season (Table 4.5) was higher at plots than watershed by almost twice, but that difference came from October rainfall events, just after terraces renewal where sediment concentration at plot scale increased. The contrary was observed in 2013 (Fig. 4.12B) where at watershed scale soil loss was around three times larger compared with plots. Plots soil loss dropped half from 2012 to 2013.

Table 4.5. Soil erosion summary and sediment concentration at watershed and plot scale. July 2012-Dec. 2013. San Isidro, San Pablo de León Cortés.

	July-Dec. 2012		**Jan.-Dec. 2013**	
	WS	**Plots**	**WS**	**Plots**
Soil loss whole period (t ha^{-1})	0.46	0.73	1.24	0.36
Soil loss all rainfall events (t ha^{-1})	0.31		0.83	
Sediment concentration (g l^{-1})				
Average SC^{WS}, whole period flow	0.12		0.15	
Average SC^{WS}, all rainfall events	0.25		0.43	
Average SCw, all rainfall events	0.41	1.60	0.61	1.71
Average SCw rainfall events > 5mm	0.78		0.98	
Maximum	>9.00	3.73	>9.00	5.64

SC^{WS} refers to g l^{-1} measure every 10 min at flume point control.
SC_W refers to g l^{-1} weighted by QT (liters) over a rainfall event.

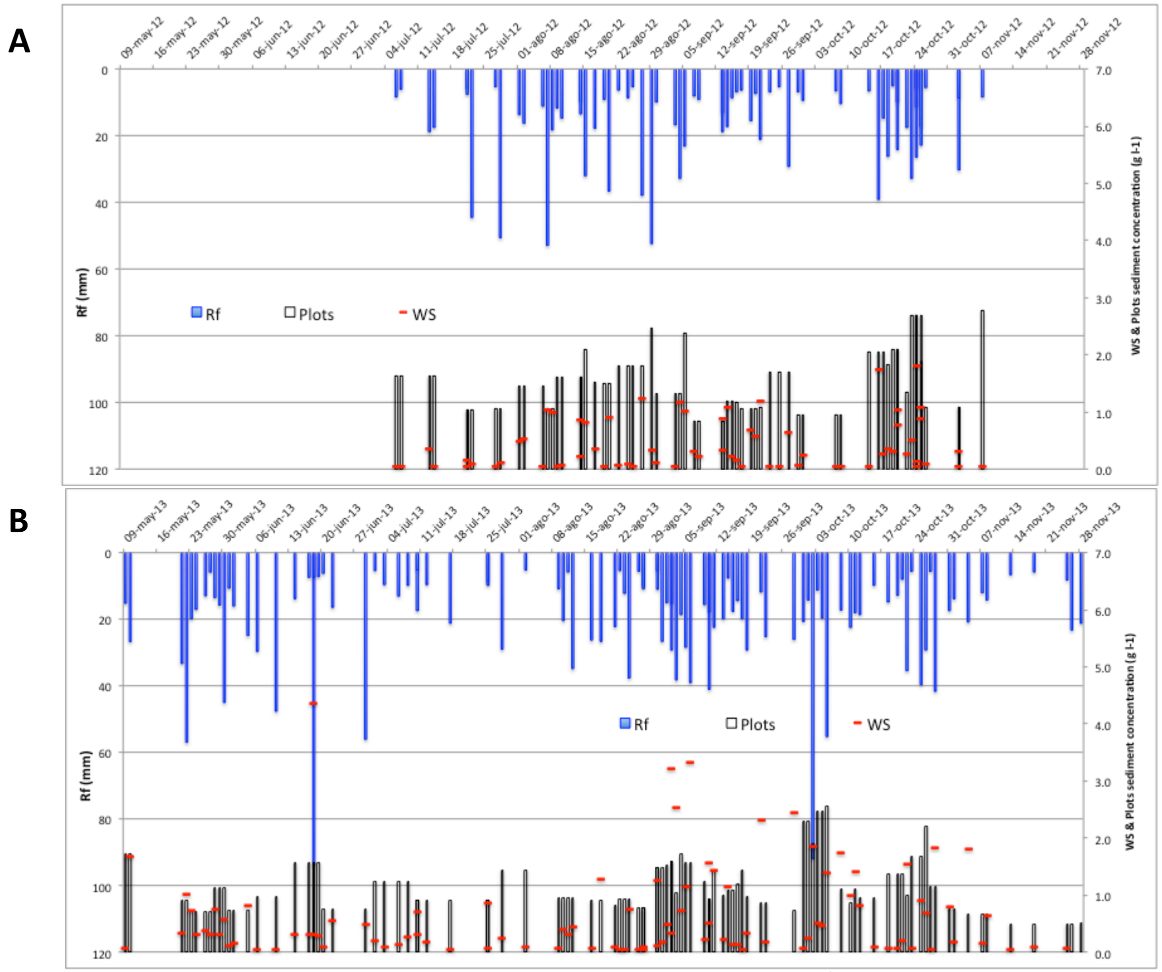

Figure 4.12. Average per rainfall event sediment concentration (g l^{-1}) measured at flume and plot level (67 and 102 rainfall events > 5 mm for 2012 and 2013 respectively). July 2012 to November 2013. Garrito watershed.

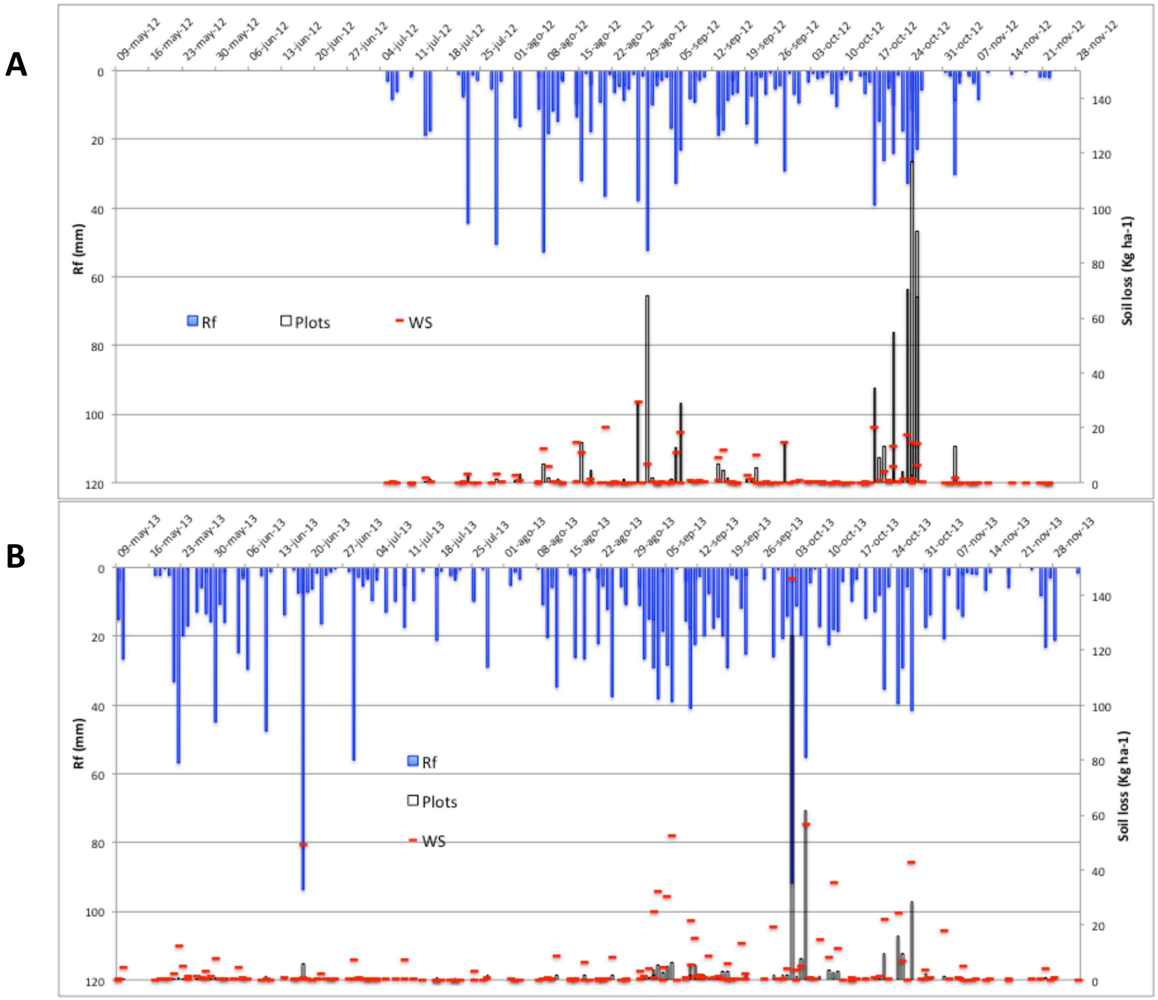

Figure 4.13. Average per rainfall event soil loss (kg ha^{-1}) measured at flume and plot level. July 2012 to November 2013 (67 and 102 rainfall events > 5mm for 2012 and 2013 respectively). Garrito watershed, San Isidro, San Pablo de León Cortés

4.3.3.3 Rainfall event scale comparison: runoff

Comparison between runoffs from rainfall events greater than 5 mm (169 rainfall events from 2012 to 2013) from watershed and plots (Fig. 4.14) shows how runoff at plots scale was higher than watershed scale for 2012 (low and right "x" marks correspond to that period). However that trend minimized in 2013 with values more even distributed to 1:1 line and easier to appreciate in the small graph (top right). Few times, runoff at plots scale was higher than runoff from watershed (Fig. 4.11B) in August and October 2012. In general, in 2013 runoff records between Plots and watershed were similar.

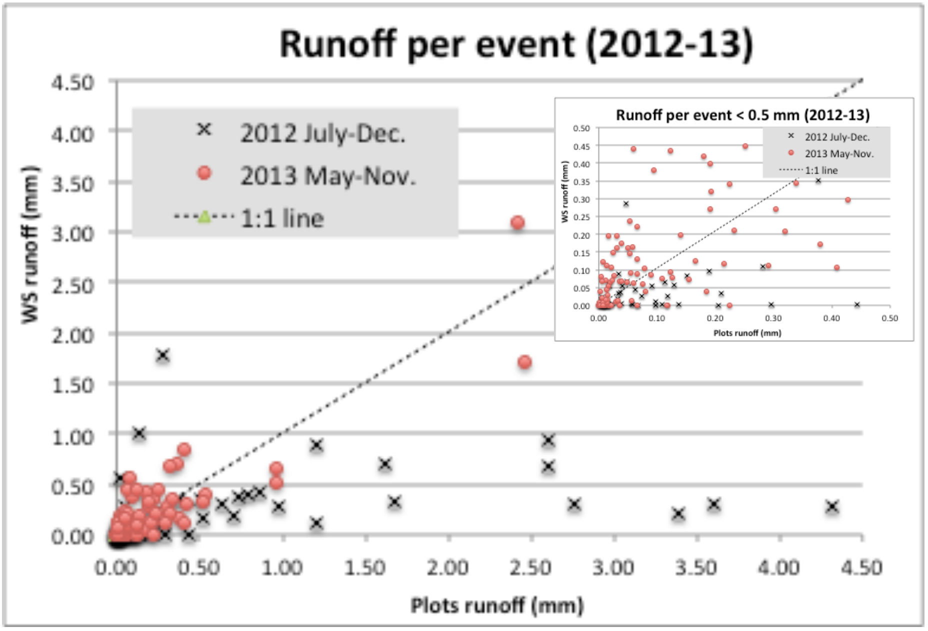

Figure 4.14. Superficial runoff comparison between plots and watershed under same rainfall events > 5 mm depth (n: 169). Upper right graph has runoff events < 0.5 mm at both scales. San Isidro, San Pablo de León Cortés

4.3.3.4 Rainfall event scale comparison: sediment soil concentration and erosion

The sediment concentration relationships between both scales were different in 2012 and 2013. The first year, especially at the end of rainy season, most of the plots sediment concentrations were higher than those measured at watershed. In 2013 the relationship turned to the opposite direction with marked differences at the end of rainy season again.

Soil erosion estimation and comparison for both scales had similar trends than runoff. Runoff is the major contributor to soil loss estimation since sediment concentration did not change drastically throughout the rainy season in 2012 with exception in October 2012. In 2013 the scenario got more dynamic since sediment concentration got higher at watershed compared with plots and runoff got larger at watershed too.

At both scales the soil losses were below 15 kg ha^{-1} per rainfall event mostly but more common higher at watershed soil loss in 2013 (Fig. 4.13B and incrusted graph in Fig. 4.16).

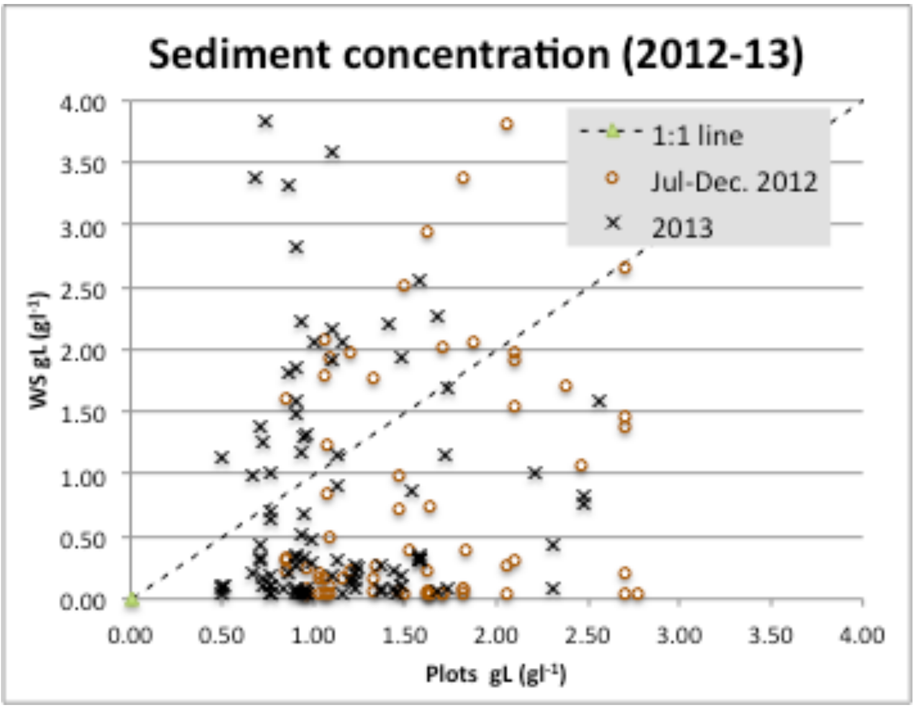

Figure 4.15. Soil sediment concentration comparison between plots and watershed scales. Second semester 2012 and rainy season 2013. (169 rainfall events > 5mm depth). Garrito watershed. San Isidro, San Pablo de León Cortés.

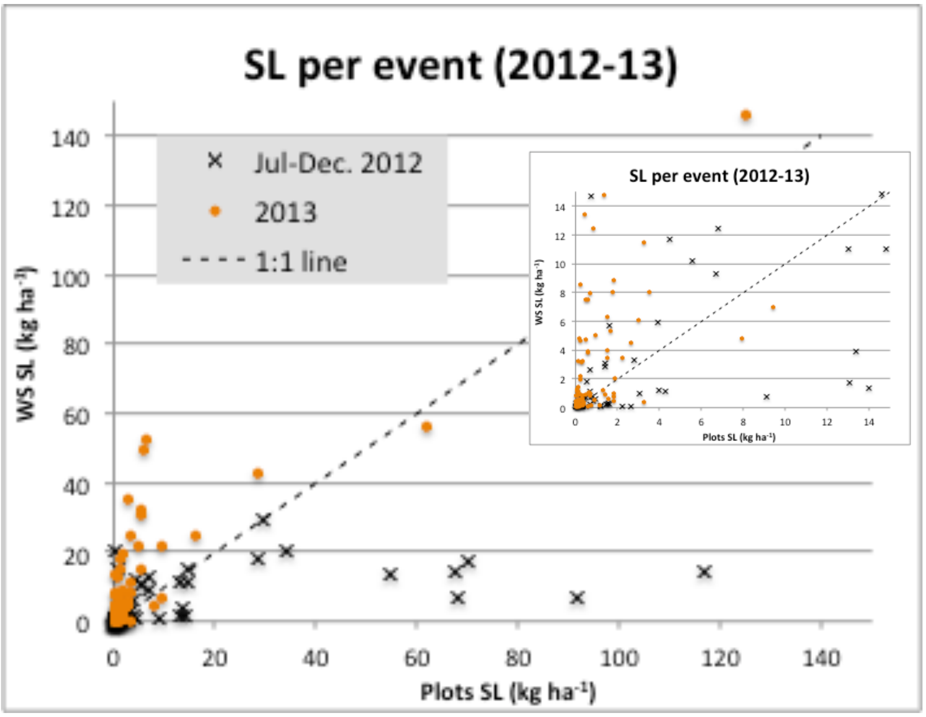

Figure 4.16. Soil loss comparison between plots and watershed scales. Second semester 2012 and rainy season 2013. (169 rainfall events > 5mm depth). San Isidro, San Pablo de León Cortés.

4.3.4 Intra-events comparison analysis for high rainfall-runoff: plots vs watershed

A total of 6 rainfall events from 2013 were chosen as representatives of three sub-periods of the rainy season: two rainfall events for the beginning, one rainfall event for middle and three rainfall events at the end of rainy season where dynamics in runoff and sediment concentration varied the most. Fig. 4.17, 4.18 and 4.19 show the intra-event dynamics between rainfall (two weather stations) plots and watershed runoffs and sediment concentration dynamic at watershed outlet. Also, initial soil water content at 15 cm depth in plots is reported per every event.

Figure 4.17 shows how rainfall intensities varied between both scales and how intensities were higher at watershed scale most of the time. It was observed from field that rainfalls usually started to the NE of the watershed and continue to West (plots direction).

Fig. 4.17A has four sediment peaks with simultaneous discharge peaks. According to Duvert et al. (2010) this means that sediments were remobilized and transported from in-channel. This rainfall event was one of the first strong one in the onset the rainy season. From same Fig. 4.17A it can be noticed that sediment concentration was not directly related with volume discharge (associated to Ro WS); the two maximum peaks corresponded with different sediment concentrations trend.

The next rainfall event (Fig. 4.17B) had the first sediment peak almost simultaneously with discharge (Ro WS in this case) and the second one was a lagging peak. The first peak still represents sediment coming from in-channel, and the second peak that is lagged represents sediment not coming from in-channel but from external sources such as croplands and roads.

On September 28th the runoff increased around double (Fig. 4.18) and runoff at plots scale now are higher than at watershed. Furthermore, the rainfall depth was half of rainfall on May 22nd. The sediment concentration peak could be higher than 9 g l^{-1} in a 10 min lap. The sediment peak and watershed runoff peak were between simultaneous and lagging peak, thus sediments could come from both sources: the stream flow itself and/or further places around the watershed.

On October 5th and 22nd (Fig. 4.19A, 4.19B) there were two different sediment concentration peaks: leading and lagging peaks which means the first sediments came from stream flow and the sediments from second peak were from around the watershed. Superficial soil water content also played a role in this runoff peaks. The higher the superficial soil water content (proxy value from plots) the faster the time response from rainfall peak to runoff peak; in superficial soil water content above 30%, the response time was 30-40 min (Fig. 4.19A, 4.19B and 4.19C), but below 30% (Fig. 4.18) it took around 70 min.

Rainfall event from Fig. 4.19C was at the tail of rainy season, rainfall event were less frequent, the superficial soil water content was 31.7% but runoff responses were low at both scales similar to onset of rainy season. The sediment concentration and runoff peaks were close to being simultaneously, thus sediments were from stream flow mostly probably.

In general, more runoff was measured at watershed scale compared to plot scale; with a clear trend to get closer as rainy season ended and as soil with higher water content prevailed. This behavior could be explained by two hypotheses: 1- the influence of roads (gravel and dirt) could have an important contribution on runoff production that was not visible at plot scale. 2- an effect of sub-surface runoff could be measured at flume point that was assumed as superficial runoff.

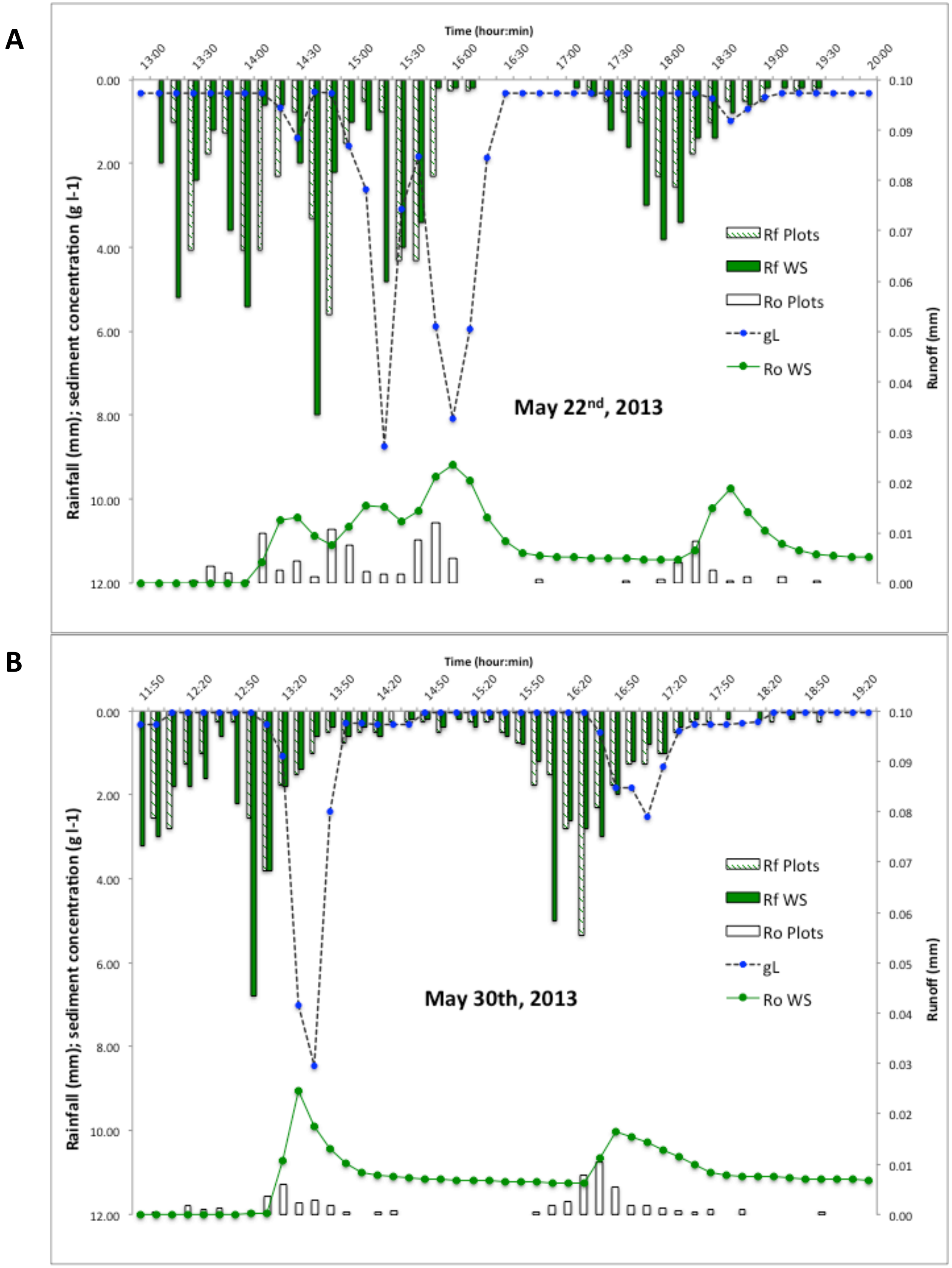

Figure 4.17. Beginning of rainy season (May 2013), 2 high rainfall events. The initial soil water contents at 15 cm depth were: (A) 23.7% and (B) 29% on May 22nd and May 30th respectively. Runoff plots and Garrito watershed. San Isidro, San Pablo de León Cortés.

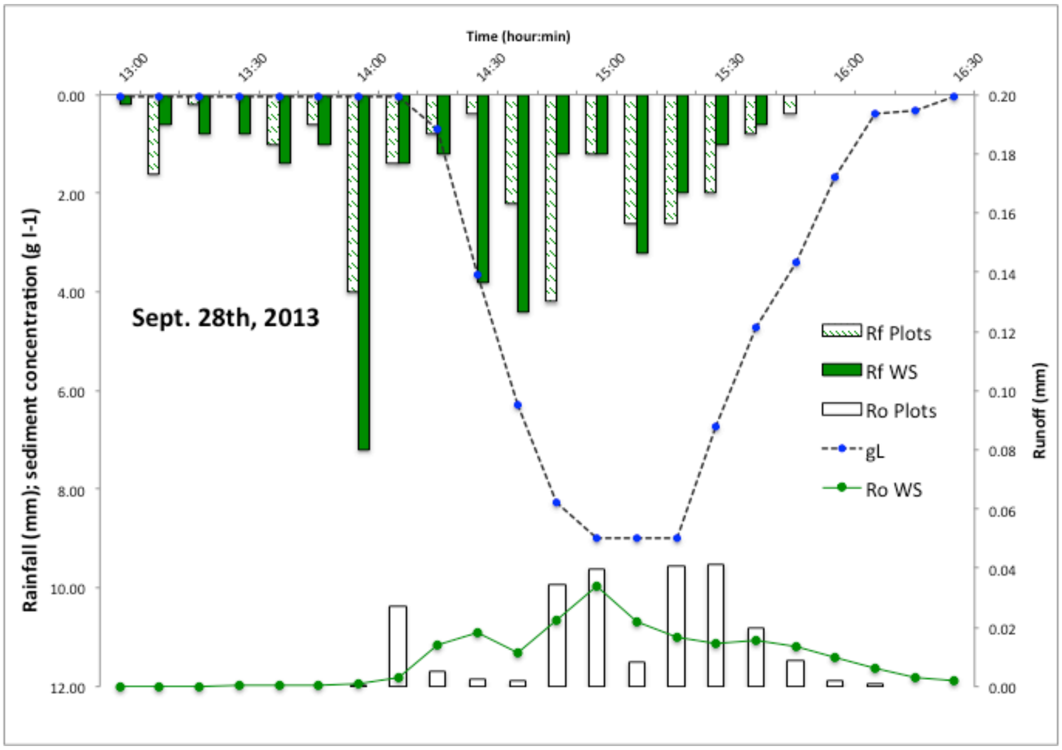

Figure 4.18. The end of middle of rainy season. The initial soil water content at 15 cm depth was: 29.2%. Runoff plots and Garrito watershed. San Isidro, San Pablo de León Cortés.

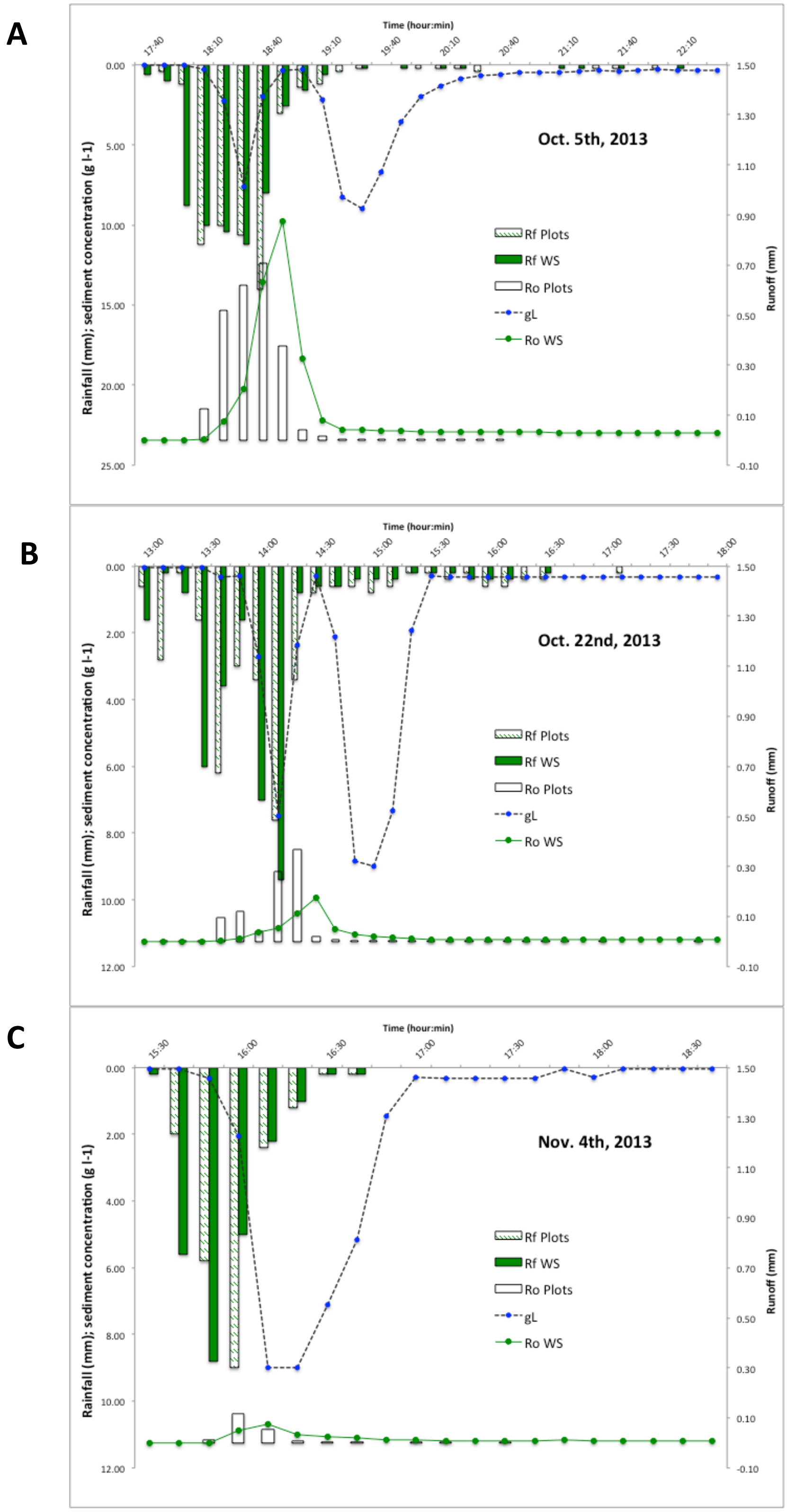

Figure 4.19. Ending of Rainy season, three high rainfall events in October (A and B) and November (C) 2013. The initial soil water contents at 15 cm depth were: 32.3%, 32.7% and 31.7% on Oct 5th, 22nd and Nov. 4th respectively. Runoff plots and Garrito watershed. San Isidro, San Pablo de León Cortés.

4.3.5 Water budget

Instruments measured rainfall and total flow (QT). Interception was estimated by applying the % of intercepted rainfall base on total rainfall depth according to Siles et al. (2010). Cannavo et al. (2011) measured 15.5% interception out of total rainfall over two years in same coffee site (under agroforestry system with average LAI= 5.96) where Siles et al. (2010) also worked. Evapotranspiration was assumed similar to reported values by Siles et al. (2010) in Central valley (1300 m.a.s.l.) with similar altitude, weather conditions and shade coffee systems with *Erythrina sp.*. The change in volumetric soil water content is shown in Table 4.6 and there were water loss from the soil getting close to zero in 2013. Finally deep percolation (plus errors) was estimated by difference or remaining rainfall and plots had higher percolation values (Table 4.6) since baseflow is included in percolation.

The high estimate percolation values might suggest the watershed could have an important leakage to another watershed or the existence of very deep aquifer. Under plots percolation estimation the quantity includes a subsurface flow not measure at both scales (plot and watershed).

Table 4.6. Water budget estimations at plot scale and watershed scale. July 2012-Dec. 2013.

Period	**July -Dec. 2012**		**Jan. – Dec. 2013**	
	WS	**Plots**	**WS**	**Plots**
Rainfall	1398	1441	2423	2586
Baseflow	181	-	394	-
Runoff	12.7	35.2	21.8	23.3
Interception	183		257	
Evapotranspiration (mm)	650		1300	
ΔSWC	-120.7	-120.7	-1.5	-1.5
Deep percolation + errors	419.0	577.5	477.2	868.2

ΔSWC: change in soil water content base on TDR readings down to 150 cm depth. In 2012 soil profile (150 cm) ended drier than beginning 2012.

4.4. Discussion

Comparison between both scales was done assuming homogenous conditions at watershed compared with coffee plots because 85% of watershed area was under shade coffee system and same crop management.

Seasonal rainfall amount and temporal distribution were important factors in terms of runoff production. The two years considered (2012-2013) were dry years but specially 2012 compared with average (1990-2009: 2460 ± 407 mm yr^{-1}). As it was mentioned in chapter 2, soil water content in superficial soil layers and low soil water storage inherits from previous season(s) had an important role on runoff production conditions. Also, rainfall intensity differences between inside watershed and plots next to it (at 10 min laps) were observed and may be another factor explaining differences in runoff production at both scales.

From the 330 rainfall events around 50% of them produced runoff, however the runoff accumulation was still low, meaning that soil had a good infiltration capacity over the periods. Rainfall events were not continuous and that pattern allowed soil to dry up faster and loading up the aquifers was moderate which can be seen in Fig. 4.10 and Table 4.6 (negative change in SWC at the end of the period) where the water table level has a steady trend not showing a large increase in soil water table over the year.

Runoff production trend was not constant in the sense that sometimes at plots scale it was higher than watershed and the contrary was also observed. Similar trend was observed for sediment concentration at rainfall event scale, where plots had higher concentrations, but at intra event analysis, the increase on sediment concentration as runoff increased was notorious (but not always proportionally). Unfortunately, it was not possible to catch sediment concentrations (flume point) higher than 9 g l^{-1} due to turbidimeter limitations.

Soil loss estimation at both scales was the product of runoff and sediment concentration, where more runoff was not always related with higher weighted sediment concentration (event scale). However, from 2012 to 2013 an abrupt change occurred in terms of runoff and sediment concentration, both decreased at plot scale and the opposite for watershed, thus watershed estimations became larger proportionally to plots. The effect of renewal in terraces in six plots out of the eight was the main possible factor leading to this change. Also, the differences could be explained partially by the trees buffer (not homogeneous distributed) along the mainstream trapping sediments and also good shade trees distributed all over the watershed that intercept part of rainfall and provided good soil coverage from pruned branches. At watershed scale also the erosion processes are widely distributed and deposition phase was still moving down the watershed not reaching the stream flow.

Water budget at both scales differed in rainfall amount (higher at plot scale) and runoff production mainly. Runoff was around three times higher at plots in 2012, but similar in 2013 despite higher rainfall events accumulation in 2013. This demonstrated how changes in management could induce changes in erosion process. As it was discuss in previous chapter, the mini-terraces renewal and reduced shade pruning had significant effect on runoff reduction and sediment concentration. These changes become more evident now that is compared to watershed monitoring.

4.4.1 Watershed scale runoff and soil loss

The general trend observed in runoff, sediment concentration and consequently soil loss at watershed scale is discussed in this section.

4.4.1.1 Surface runoff

Seasonal superficial runoff response to rainfalls at watershed scale was very low (0.9% of rainfall each year) due to dry conditions in 2012 and great soil coverage at watershed due to shade coffee system and similar litter conditions as in runoff plots. The good soil coverage despite the high gradients (50-60% watershed average slopes) corresponds to one of the main recommendations for erosion reduction (Northcliff et al., 1990; Descheemaeker et al., 2006; Blanco-Sepúlveda et al., 2015; Labrière et al., 2015).

In terms of runoff threshold production, as it was indicated, runoff records started around 5 mm which is similar to the rainfall threshold of 4 mm for runoff production found by Huang et al. (2001).

The high rainfall events (especially > 20 mm) initiated fast response in runoff production, however the increase in stream flow level (peak flow) lasted for a short period (from minutes up to almost 2 hours). The watershed had a quick response in runoff and soil loss production but infiltration at watershed level seems to be very high. Possibly, under higher and more frequent rainfalls, such as normal rainy season or under “La Niña” phenomenon, the erosion process gets stronger and higher soil loss rates would be measured.

Most of runoff could come from roads, human paths and gullies as other studies have reported (De Vente and Poesen, 2005). However, even assuming a conservative 50% of runoff coefficient (at rainfall event) for bare soil areas such as gullies and roads (6.81% of total area, Table 4.1), the hypothetical runoff coming from those exposed soils would be larger than measured at flume point. This means that gullies and roads produce less that 50% runoff or/and they are partialy disconnected from the main stream, with some re-infiltration places. Also, weeds in gravel roads could function as runoff barriers (road borders) and small filter strips. Weeds on dirt roads increased soil protection to rain drop impacts and increased rainfall interception. These two aspects from coffee roads have not been mentioned in other soil erosion studies under coffee.

We observed a dynamic where runoff was higher at WS scale beginning rainy season 2012 compared to plots, and then this relationship reversed. The high plots runoff values were measured ending of rainy season in 2012, corresponding with just after time terraces were renewed and more bare soil was present at plots. In fact, the whole flat terrace part became uncovered. Terraces renewal seems to increase runoff at least temporary until soil coverage recovers. That runoff increase was not observed at watershed since around of 50% of the coffee area had terraces renewed in 2011 and the effect on runoff increase should not last more than a few months.

Watershed discharge responses were fast when soil got wetter (end rainy season) and moved back to steady flow fast as well probably due to watershed high infiltration reflected by rainfall events. This high infiltration capacity from watershed could be the consequence of many factor acting together, such as coffee coverage, good litter soil coverage, shade tress protection and roots improvement on macroporosity (also from coffee plants), still remaining riparian sector working as filters, rainfall interception and soil profile improvement.

4.4.1.2 Sediment concentration

It was low at both WS and plot scales, but lower in average at WS scale (0.41 and 0.61 g l^{-1} for 2012 and 2013; Table 4.5). A coffee runoff and sediment concentration study under shade coffee and 55% slope in Puerto Rico also found sediment concentration around 0.16 to 0.24 g l^{-1}. The shade coffee systems offer very good soil coverage in addition to practices such as pruned material maintained in the field helping to progressive terraces formation. Blanco and Aguilar (2015) demonstrated how soil erosion decreases as soil coverage increases even using visual evaluation.

4.4.1.3 Soil loss

The increase from 0.46 to 1.24 t ha^{-1} yr^{-1} in soil loss from 2012 to 2013 was a consequence of higher runoff production due to more rainfall (25% increase) and 50% higher average sediment concentration at flume control. The erosion rate seems to be in a very low range, however according to Labrière et al. (2015) extensive literature review from tropical sites reports, the soil erosion rate gotten in Garrito watershed is around average values reported from shrublands (54 reports) and tree-dominated lands (579 reports) with 0.22-0.60 t ha^{-1} yr^{-1} and 0.21-0.36 t ha^{-1} yr^{-1} respectively, and for cropland the average from 1364 reports was 0.66-1.02 t ha^{-1} yr^{-1}. Soil erosion values quite high from steep lands were also reported in the literature, such as Tangtham (1991) who measured soil loss from 5 to 90 t ha^{-1} yr^{-1} under soil slopes between 20 and 80%. Gafur et al. (2003) measured 11.5 to 41 t ha^{-1} yr^{-1} under shifting agriculture in Bangladesh. Hacisalihoglu (2007) from vineyards plots under slopes greater than 35% measured up to 6.47 t ha^{-1} yr^{-1} in 14 years in a row data collection. These high erosion rates can be explained by the reduced soil coverage compared to shade coffee system.

4.4.2 Scale effect in runoff and soil loss

A comparison of both scales in terms of runoff, sediment concentration and soil loss and how they differed or behaved similar to each other is discussed.

4.4.2.1 Surface runoff

Attention should be paid, when comparing results from different spatial scales, to the associated temporal changes (Blöschl and Sivapanal, 1995). There are permanent sectors inside the watershed that did not change much over the season: roads, gullies (it did not increase much over a rainy season) and infrastructure (warehouses, shelters and houses). The latter had no significant influence in this study since there is only one small warehouse located under trees. However, a very evident and important factor is the change in soil coverage (litter, grasses, coffee and canopy from shade trees). The soil coverage, as it was mentioned from previous chapters did not change much over the year; it dries over dry season, but did not disappear and coverage remains (also dead materials). The canopy protection was affected by producer since they prune twice a year the shade trees. However, those branches were left all over the alleys and improved soil coverage. Consequently, soil coverage from shade coffee system in the watershed is quite similar as it is at plot scale. Driven factors for high runoff production should come from permanent factors such as exposed areas. One potential source of high runoff was bare soils where runoff coefficient must be higher than covered soil. For example, Xu et al. (2013) from 2 m^2 plots on 45% soil slope measured much less superficial soil runoff under soil covered by vegetation than uncovered (6.2 and 30.3 % respectively).

Two trends were observed from the data, from plot to watershed the runoff increased (in 2013), but the contrary was observed in 2012 (Fig. 4.14). Some studies have reported that runoff decrease as area increases (plot to watershed). Descroix et al. (2008) mentioned that runoff decreases as watershed increases up to 5000 ha and after that size runoff increases. Even more, they said sheet erosion was 2 times larger than gully erosion at hillslope scale. Also, Cerdan et al. (2004) observed in low slope soils (North of France) that runoff coefficient decreased as area augmented, from 450 m^{-2} up to 90 ha the runoff index dropped 3 times and from 90 ha up to 1100 ha it dropped 10 times. Other studies reported the contrary: Le Bissonnais et al. (1998) measured a higher runoff coefficient at watershed scale than plot (10% and 2% respectively) and even more runoff coefficient increased from 10 to 50% under rainfall intensity increase from 1 to 9 mm h^{-1}. Gómez-Delgado et al. (2011) reported from other watershed sites runoff coefficient values between 3 to 10 % and at plot scale from 2 to 6% in Costa Rican experimental sites reported by Harmand et al. (2007), Siles (2007) and Cannavo et al. (2010).

Different rainfall depths categories had effects in runoff production dynamic depending the scale. There was a higher superficial runoff at watershed than plots in 2013 that got stronger trend under rainfall events greater than 20 mm. Albeit, under the few rainfall events > 40 mm in 2013, plots runoff increased drastically and even higher than watershed. The management practice that coincides consistently with increases in runoff coefficient at both scales was shade pruning. This lost in canopy coverage (and interception capacity) even when coffee coverage was considered good (coffee LAI: 3.92 ±0.68, Meylan 2013) the effect is reflected in runoff increase. The change was more evident under rainfall events above 20 mm. Also when mechanical weed control was done in the watershed in 2013 middle end of September (Table 4.2, Fig. 4.11B) the runoff in October 5th under a 55 mm rainfall changed pattern compared with previous deep rainfall events, now runoff increased at watershed again, no other practice was applied in the watershed.

The soil spatial variation (weed coverage, water content, physical properties, lithology) plus the weather variation in terms of different rainfall intensities in short distance triggered different runoff production all over the watershed. As Descroix et al. (2002) pointed out, by following 5 watershed in Mexico from 90 sites, they determined that spatial variability in hydraulic conditions is almost as high at 1 m^2 scale as 100 ha; soil lithology and soil surface features have a high relationship with soil variability. However, runoff production seems to be highly influenced by plot size according to Gomi et al. (2008). They measured it under steep hillslopes in Japan from two size plots and observed 2-10 times higher runoff in small plots (1 m^2) vs large plots (192-216 m^2). The runoff coefficients for small plots were between 20-40% and for large ones was 0.1-3%. Santos et al. (2014) in Guatemala measured less than 10% runoff coefficient under 75 m^2 and 150 m^2 plots with sugarcane over a year period. Vahrson and Cervantes (1991) measured 1.3 % and 0.6 % runoff annual coefficient under two coffee systems (with and without shade trees respectively) and 60% soil slope Alfisol from 134.5 m^2 plots. Verbist et al. (2010) got runoff coefficients of 10-15%, 4% and 4-7% for coffee monoculture, forest and shade coffee respectively.

Zhu and Zhu (2014) from different length plots (7 and 20 m) observed that superficial runoff was always higher under short plots compared with long ones. Podwojewski et al. (2008) measured 1-2% runoff coefficient from 1 m^2 plots under forest which is close to what was measure under two years period in this study as annual estimation (Table 4.6) with 0.9% and 0.9-2.44% for watershed and plots. This shade coffee system seems to behave as a similar forest system in terms of runoff production, at least as annual estimation. The higher runoff coefficient (2.44%) from plots was from 2012, once the terraces stabilized moved down to 0.9%.

Another aspect that was not possible to measure, but which is often mentioned, is sub-surface runoff that could become an important source of runoff. At plot scale it is not likely and at watershed scale it was mixed with baseflow and runoff from long rainfall events. Xu et al. (2013) measured subsurface runoff and determined that it was lower (proportionally to superficial runoff) in bare soil than under soil covered by vegetation. The latter was reported between 60-90% by Liu et al. (2005). They also observed a decrease of subsurface runoff as rainfall intensity augmented. Weiler et al. (2005) stressed that subsurface runoff plays an important role under steep lands and humid environments. Then, the monitoring of this component would be a recommendation for future studies.

4.4.2.2 Sediment concentration

Sediment concentration was not always positively related with total discharge (QT), which was also observed in other studies. Verbist et al. (2010) observed no linear relationship between sediment concentration and runoff discharges. On the other hand, Calhoum and Fletcher (1999) from a 54.4 km^2 watershed in Hawaii measured sediment concentrations between 0.01 and 0.06 g l^{-1} and observed an increase of sediment concentration as watershed discharges increased. Le Bissonnais et al. (1998) observed that sediment concentration over a discharge corresponded with discharge peak. In Garrito watershed, when there was a positive relationship it could be related with streambed cleaning, and if rainfall continued, the next discharges were cleaner water in terms of sediments suspension even under other discharge peaks. Similar QTs had different average sediment concentrations. For example QT: 212, 210 and 212 m^3 had average SC of 0.45 ± 0.20, 0.75 ± 0.25 and 2.54 ± 0.54 respectively. Soil coverage dynamics had an important role in these changes on sediment concentration at flume checkpoint. Xu et al. (2013) from 2 m^2 plots under 45% soil slope observed an increase of sediment concentration as simulated rainfall intensity increased and values were below 2 g l^{-1} under vegetative coverage and vegetative removal (partial), but between 5.5 and 10.5 g l^{-1} under hoed soil (bare soil).

The average sediment concentration per rainfall event (SC^{WS}) at outlet watershed was always below 1 g l^{-1} due to high dilution throughout the rainfall event and quick increases and decreases in sediment concentration per event. Solano (2010) reported a discharge curve in Pirris watershed where sediment concentration (172 samples over 1978-1996 period) oscillated between 0.01 to 5 g l^{-1}. Also Verbist et al. (2010) measured sediment concentration from tributaries lower than 5 g l^{-1} and in the main river (Way Besai) with values between 0.25 and 0.50 g l^{-1} and peak discharges with 1 g l^{-1}. Duvert et al. (2010) measured sediment concentrations between 0.01 and 100 g l^{-1} with a trend of decreasing over the rainy season. The same trend was also observed in Garrito watershed but not reaching those maximum values.

In 2012 the sediment concentration ratio between plots and watershed tended to be large especially at the end of 2012. This drop in sediment concentration at the flume could be due to a dilution of surface flow with clean base and sub-surface flows. Also, the terraces renewal in the plots produced an evident increase on sediment suspension not just due to bare soil, but superficial soil disturbance (by machete and by people walking). In 2012 on average the sediment concentration was almost 12 times higher at plot scale (max. SC ratio = 55) than watershed.

In 2013 the ratio of sediment concentration at plots with respect to watershed dropped to almost 6 times (max. SC ratio = 30). Le Bissonnais et al. (1998) reported that from plots and watershed comparison, the sediment concentration at watershed outlet was always lower (10-30 times) than plots.

4.4.2.3 soil loss

At watershed the soil loss (from 169 rainfall events > 5 mm) in average was around 2 times higher than plots in 2012, but in 2013 this ratio increased to 6.5. However annual soil loss in 2012 was higher at plots but the contrary in 2013 where at plots it dropped 50% and at watershed increase around 150%. Zhu and Zhu (2014) at plot scale from two length plots (7 and 20 m) measured in general more soil loss under long plots than short ones and different soil slopes. The latter could mean an increase in soil loss as area increases, however many other factors of watershed scale affect the trend as it is discussed later.

In comparison with other studies, Le Bissonnais et al. (1998) measured at plot scale (1, 20 and 500 m^2) 2 t ha^{-1} and 0.3 t ha^{-1} at watershed scale where 90% of soil loss was from runoff peaks period. Blake et al. (2012) measured higher soil loss rate at plot scale than catchment scale (145 ha with slopes between 3.5 and 27%. Santos et al. (2014) in Guatemala got sediments production under rainfall events greater than 10 mm depth at plot scale under sugarcane and tree plantations (*Eucalyptus* and *Ficus elastica*) over a year period. They estimated from plots results than around 94% of a watershed (300 ha) where they worked the soil loss was below 10 t ha^{-1} yr^{-1}. Verstraten and Poessen (2001) from 26 small-cultivated watersheds (10-10000 ha) in Belgium measured soil loss (as area specific sediment yield) between 0.4 to 20.6 t ha^{-1} yr^{-1} with a trend of dropping soil loss as watershed area increases but the contrary if only total sediment yield is considered (not by area). Chappell et al. (2004) measured 5.92 t ha^{-1} yr^{-1} in one year and 44 ha watershed where 3.52 t ha^{-1} yr^{-1} was produced by only one extreme rainfall event, which was also observed by Evans`s work (1997) where one extreme rainfall event produced almost 60% of annual soil loss. Adediji (2006) from 19 first order basins in Nigeria measured over a year an average of 0.3, 0.18, 0.17 and 0.14 t ha^{-1} yr^{-1} for non vegetated basins of study area, field crops, cocoa dominated and forestall basins respectively.

From previous study under same Pirrís watershed, Solano (2010) measured plots soil loss under different coverage (coffee, grass and forest) and slopes (30-60% slopes for coffee plots and grass: from 0 to 60% for forest plots). Coffee plots had 10.9 t ha^{-1} yr^{-1} soil loss; grass plots had 0.11 t ha^{-1} yr^{-1} and forest had lower soil loss values than grass coverage. The experimental plots and watershed used in this study is located under a Pirris sub-catchment named #9 (according ICE own identification) with 39.85 km^2 and the average annual estimated soil loss (from sediment measurement at watershed outlet) was 22.81 t ha^{-1} yr^{-1} from 1978-1996 (Solano 2010). Under the same Pirrís watershed (27494 ha) the estimated soil loss was 7.75 t ha^{-1} yr^{-1}. Another similar study in Costa Rica was established by Vahrson and Cervantes (1991) measuring under two coffee systems (with and without shade trees) and 60% soil slopes on a Alfisol (Udic Haplustalf) and a soil loss rate of 1.36 and 0.17 t ha^{-1} yr^{-1} respectively. These soil loss rates were similar to ours.

On the other hand Verbist et al. (2010) measured watershed erosion 3-10 times greater than plot erosion. Furthermore Verbist (2010) measured same (no significant different at 1% level) soil loss under shade coffee and forest (plot scale) with 0.28 t ha^{-1} yr^{-1}. This soil loss rate is close to what we measured and could be a signal that shade coffee systems (with good soil coverage) are relative good systems in terms of minimum soil loss.

Our data is from plots and one watershed, so we could not test different size effect, but from two scales we already saw this trend can move both ways. As De Vente and Poesen (2005) determined from many watershed data that soil loss increased as area augmented from 0.1 ha to 10 ha (rill and interrill processes dominated under 5 ha and gully dominated over 5 ha) and decreased after that size related to other processes not included at plot scale such as gullies and river bank-bed erosion. Descroix et al. (2008) mentioned that soil loss decreases as watershed increases up to 5000 ha and after that size it increases. Verbist et al. (2010) estimated 9% of watershed soil loss came from landslides, river bed-bank erosion, footpaths and roads. The latter also reported by Bruijnzeel (2004) as 54% of total soil loss from 5% watershed area only. The soil loss dropping as watershed area increases was also mentioned by Walling (1983). However, either it increases or decreases; the relationship is not linear with respect to basin area (Verbist, 2010).

Verbist et al. (2010) observed much higher soil loss at plot scale over the first year than the next four years study time probably due to plots disturbance, which was also mentioned by Widianto et al. (2004). At watershed scale they determined that around 20% of total area produced little more than 60% of soil loss where watershed erosion was

3-10 times higher than plot scale, which was also reported by Bruijnzeel (2004) under a volcanic soil in SE Asia.

Another component that was not measured (if it was present) was the bed load (heavy soil material moved by flow water that moves deeply. The bed load is highly variable, from Verbist et al. (2010) they mentioned 10% of total soil loss according to consultants in Indonesia, but they used 26% instead. In Pirrís watershed Solano (2010) applying two methods (Einstein-Brown and Meyer-Peter) got 14.6 and 19% respectively. However, even applying this correction for both years at watershed scale the soil loss is still under 2 t ha-1 yr-1 which is a very light rate according to Morgan (2005).

Some studies measured linear erosion that was not measured in our study but observed (gullies source meanly). It could become an important source of soil loss but included at flume measurements. Chaplot et al. (2005) from 62 ha watershed (48-62% soil slope) measured an average soil loss of 1.3 t ha^{-1} yr^{-1} (2001-2003) considering riling and gulling as linear erosion only, but if just crop area was considered, the soil loss would rise to 9.5 t ha^{-1} yr^{-1}. From one-year total sediment load at watershed, the estimated soil loss was 2.8 t ha^{-1} yr^{-1}. Poesen et al. (1996) from 25 ha watershed observed that 30-80% of total erosion budget corresponded to linear erosion (channels); DiCenzo and Luk (1997) reported 88% linear erosion of total soil loss in Tropical China. Duvert et al. (2010) from 3 watersheds (3, 9.3 and 12 km^2) measured 9-15, 6-8 and 0.3 t ha^{-1} yr^{-1} respectively where the differences were due to gullies rather than erosive indices. After all, most of the annual soil loss is a product of one or few high magnitude rainfall events (Mano et al. 2009; Duvert et al. 2010) as it was also shown in chapter 2.

4.4.3 Water Budget

Hydrological measurements reflect low runoff (0.9% of rainfall for 2012 and 2013) and baseflow output (12.9 and 16.2% of rainfall for 2012 and 2013 respectively) from watershed on an annual data basis.

Gómez-Delgado et al. (2011) from volcanic soil watershed of 90 ha reported a baseflow around 56% of annual rainfall which was similar (59%) reported by Fujieda et al. (1997) in Brazil from 56 ha Ferrasol watershed. However, Charlier et al. (2008) under volcanic soil in Guadaloupe island reported 17% and Kinner and Stallard (2004) in Panama reported 20% of annual rainfall under forest, which is in the same range than our measurements.

Gómez-Delgado et al. (2011) summarized water budgets components results from different authors at watershed scale including their research. The size of watershed was between 10 ha and 90 ha. The climate for those sites was Humid tropical or Humid subtropical including Brazil, Panama, Guadeloupe (island) and Costa Rica. Annual evapotranspiration varied from 25 up to 53% of annual rainfall. In our study we applied Siles et al. (2010) estimation for evapotranspiration due to similar altitude, annual rainfall and coffee systems. The estimation corresponded to around 45% and 53% of rainfall in our watershed for 2012 and 2013.

This watershed had very low annual runoff production. However, at the scale of rainfall events analysis it reaches a maximum of 15.5% runoff coefficient at plot scale and 5.5% runoff coefficient at watershed scale. This difference reflects how the watershed has a stronger capacity to diluted high rainfall events effect due to more variability conditions inside the watershed.

Our budget indicates that a high percentage of rainfall may infiltrates (21.3 and 19.6% of rainfall for 2012 and 2013) and seems to percolate to deeper aquifer or close watershed. According to people from the watershed the main WS stream dried out completely around 50 years ago, and it was very close to dry out again in 2012. Also they affirmed that after two strong earthquakes in 2010 (May 20th and 31st) the mainstream source of this watershed tended to dry out more often over dry season. Thus, deep infiltration probably happens and leaking to another watershed due an internal rock crack. At the same time, total rainfall has decreased since 2011 with respect to average.

4.5. Conclusions

Comparison between plots and WS measurements of runoff and soil loss is complex due to many factors affecting this dynamics. The trend in one year changed to the next one. Coffee practice at both scales seems to have an important effect on runoff and sediment concentration production. The terraces renewal had an effect on increase in plot runoff and sediment concentration just after the rectification. However, a year later, with more rainfall, the effect was a reduction on runoff and sediment concentration too. At short run effect was negative, but it was that way since the terraces were renewed just 15 days prior the peak of rainfall season (even under a dry year as 2012 was). The renewal should be done after the rainy season ends or beginning of rainy season (May or June).

Average low sediment concentration seems to be consistent at plot and WS scale even when there were peaks (flume observations) and values moved back to low concentrations relatively fast (< 20 min).

Besides soil heterogeneity also mentioned by other researchers (Saison et al., 2008), rainfall variability played an important role since rainfall depth varied from WS to Plots. During some rainfall events the difference between rainfall intensities measured at watershed and plot weather stations was important which was consistent with changes in discharge differences at both scales. Watershed studies that cover large watershed areas could be affected by this variability in spatial rainfall distribution.

Finally, the water budget analysis shows that this watershed had very low runoff and high percolation. It is suspected that lithology is not continuous and could be cracked around the watershed, which could avoid soil profile to saturate in some areas.

Chapter 5: General discussion, conclusions and perspectives

5.1 Discussion on the experimental conditions

5.1.1 Soil and topography

The results presented in this thesis are based on field plot measurements at farm level under real management conditions and on watershed scale monitoring. The average soil and topographical characteristics were similar under both scales.

Dominant soil type is Ultisol (Soil Survey Staff, 2010), Ferrasol (FAO, 1998) or Acrisol (W.R.B., 1998), which represents 38% of total Pirris watershed area (Chinchilla, 2011). It contains 47 ± 3.1 % average clay and 30 ± 2.3 % silt soil content for the first 40 cm depth, and effective soil depth around 100-150 cm. This high clay content gives to this soil some resistance to soil erosion, however soil aggregate stability measured in plots site was low (0.86 ± 0.28; Nespoulous, 2011). Soil characteristics, such as layers depth and thickness, varied along the hill where the plots were located and over the watershed due to different effects of soil erosion and consequences of previous land use (grassland 35-40 years ago). These irregular subsoil conditions (shallow soil sections) could trigger high runoff production on specific spots inside plots and watershed as one of the sources of runoff variability (Descroix et al., 2001). The water storage status and capacity associated to these changes in different soil layer thickness played a relevant function on infiltration capacity (directly related to runoff production) as it is discussed later on in this chapter.

Slopes were in the range 50% to 75% both for experimental plots and watershed fields. This represents extreme conditions for cultivation, even for coffee, as it corresponds to a limit for safe displacements within field and also a limit for slopes stability (mass movement would be very frequent for steeper slopes). However the presence of mini terraces facilitates human movement in the coffee plantation for management activities and harvesting. At the same time, these mini terraces affected runoff production and sediment concentration.

The soil has irregular surface (at plot and watershed scale) that facilitates superficial runoff finding preferential paths. This situation obliges to concentrate flows that acquire high capacity of detachment and transportation. At the same time it facilitates reaching small soil cracks increasing soil infiltration and decreasing expected runoff production.

At plots site, the presence of mini-terraces (made by shovel without homogeneous dimensions, i.e. not same flat section width along the alley and different riser heights since they were made by hand just looking for soil flat condition) was a factor that also impacted runoff production. The slope segments where the coffee plants were planted were almost flat with some signals of soil accumulation probably due to mini-terraces slides along the years and sediment retention induced by coffee and shade trees branches left on the ground perpendicular to slope and hold by coffee trunks. These structures could have an important role on runoff control coupled with soil coverage (superficial and aerial). It was expected that the renovations or rectification of these mini-terraces would reduce superficial runoff since soil slope gets to zero or very flat. However probably due to the coverage lost in terrace flat section, and bare soil, the runoff speeded up and also the sediment transported out of the plot. After the stabilization (1 year) of risers and the recovering in soil coverage by weeds and vegetative material from coffee and shade trees, the runoff decreased and sediment concentration too.

5.1.2 Climate: rainfall and soil moisture

Weather conditions were very important in terms of water availability for the systems and how the rainfall energy acted over the coffee plantation.

The weather regime is Ustic, where the dry season goes from December to April. The rainy season concentrates from May to October with its peak in October, where a combination of high soil water content and long rainfall events triggered off superficial runoff. Between 60-70% of annual runoff and 60-80% of annual soil loss occurred during October in the three years evaluated. The concentration of dynamics in one month imposes to be very careful with the practices applied in this time. The surface soil coverage and canopy coverage must be high and not altered during this short period of rainfall concentration. However due to El Niño/La Niña phenomena (ENOS) and irregular rainfall pattern in 2013, the normal rainfall distribution was not present and rainfall event were scattered. The latter allowed the soil to dry out and consequently the infiltration capacity remained high most of the time when next rainfall event occurred.

Annual rainfall was average in 2011 and 2013, but in 2012 the weather conditions was drier than average (1990-2009: 2460 ± 407 mm yr^{-1}). This condition of water supply shortage affected soil water storage inherited to next rainy season and a water storage deficit at the end of 2012. This was an important finding in the sense that individual rainy years analysis could be incomplete or misleading. A soil profile drier than normal conditions needs more water in order to reach saturation conditions, which happened in 2013 and runoff production was low most of the time. This low soil water content allowed a high soil infiltration capacity at the soil surface for longer times. This temporal interaction between rainfall and soil moisture should be always taken into account. For example concluding that soil erosion potential of the study site is very low on the basis of the coffee plot results in 2013 only, would lead to an underestimation. In 2011 with similar cumulative rainfall, the soil loss was almost 4 times higher than registered in 2013 for the same plots measurements without management changes in the three years.

The two weather stations measured sometime different rainfall depth for same events. One weather station was in the middle of the plots and the other one around the middle of the watershed and approximately a difference of 500 m in straight line was from one to the other. Only few times there was rainfall events recorded in the watershed but not in the plots. The rainfall differences were not only in total depth, sometimes with similar depths the inside rainfall pattern differed. This difference represents the spatial variability that could occur in a watershed even in short distances as it was also mentioned by Descroix et al. (2001).

5.1.3 Soil coverage

Soil coverage (live and dead material) had a relevant influence on soil erosion control (Truman et al., 2005; Descheemaeker et al., 2006; Anikwe et al., 2007; Zhou et al., 2013; Blanco y Aguilar, 2015). At plot scale, it was evaluated throughout 2013 and low variability was measured from medium to high coverage level (three level visual evaluation). In addition, LAI measurements indicated that the coffee coverage was in general good for soil protection besides the shade trees coverage. The coffee density in plots site was high (aprox. 7700 plants per ha) which provides good soil coverage. In this aspect, Dariah et al. (2004) and Hairiah et al. (2004) found (in coffee density of 5000 plants ha^{-1}) that only the coffee coverage could be enough for controlling erosion to tolerable level. At plot scale the soil erosion process seemed to be influenced by soil coverage that protects very effectively against the impact of rainfall drops and reduce the speed of superficial runoff allowing more time for infiltration process and decreasing the potential of soil particles transportation. However, under strong rainfall events (> 40 mm) the runoff increased especially under very wet soil conditions (>35% in soil volume).

Soil in coffee plots and watershed received frequent contributions of coffee leaves and branches, shade trees (*Erytrina sp*. and *Musa sp*.) leaves and branches after pruning and weeds material after mechanical control with machete. There were bare soil spots under coffee canopy but still protected by coffee and shade trees. This important contribution to soil coverage material becomes a relevant aspect on soil protection against erosion as Labrière et al. (2015) found reported from many soil erosion studies in the Tropics.

5.2 Runoff and erosion processes within coffee field on steep slope

Soil erosion under steep slope at plot scale was lower than expected. The largest annual soil erosion rate over a three years evaluation in a row did not overpass the 4 t ha^{-1} and dry years condition had an important effect. The average annual soil loss was around 1 t ha^{-1} yr^{-1} that classifies as light erosion (FAO, 1979). This erosion rate could be considered low, but even when there is not precise information about soil formation rate, the soil formation rate must be lower than the erosion rate, thus effort in soil erosion reduction is still necessary.

The moderate annual soil loss was related to the systematically low sediment concentration also reported in other studies (Presbitero et al., 1995; Verbist et al., 2010). In addition, the correlation between rainfall intensity and sediment concentration was low (reference plots annual average between 1.31 ± 0.69 and 1.47 ± 0.40 g l^{-1} for 2013 and 2012 respectively). No significant increase in sediment concentration was observed as runoff increased under extreme rainfall events. The factors that might explain this trend of low soil detachment are: (i) less effective rainfall per area due to a steep slope which allowed to capture around 85% of total rainfall per area; (ii) a high coffee density in addition of shade trees, effectively protected the soil surface from the impact of high energy raindrops; (iii) a very good soil coverage over the entire rainy season (iv) a good soil infiltration capacity observed even during extreme rainfall events. (v) presence of mini-terraces, which segmented the total plot length therefore the soil aggregates transportation, thus reducing opportunity for aggregates or soil particles breakdown as showed by Wang et al. (2014). The mini-terraces renewal induced a “crisis” period for 2-3 months during which the protection and stability was reduced until they stabilized again over a year. This increase in runoff and soil loss after the mini terraces rectification occurred just before the October rainfall peaks that could intensify the effect on runoff and soil loss. This experience demonstrated that the mini-terrace renewal should not be done in that time; it would be better to do it at the beginning of rainy season or just after the October.

The infiltration model (Diskin and Nazimov, 1995, 1996) for simulation of infiltration and runoff at intra-event rainfall explained runoff better than inter-rainfall data. The model was theoretical but fitted well enough with the runoff observed in this steep land conditions. The rainfall intensities and the initial soil conditions were the main factors that explained runoff variability at intra-event level. The rainfall intensities above 40 mm h^{-1} fitted the model better, which was a limitation for its application. However, it could be adjusted to specific site conditions, modifying soil water storage capacity and the range of the highest and lowest soil infiltration capacity (fc and fo) that could vary a lot due to heterogeneity in the field.

There are three possible explanatory variables that might justify the remaining discrepancy between data and modeling. First, the rainfall plot interception area where runoff came from could be lower than the assumed total plot area and perhaps only part of the bottom plot area contributed to runoff record. The contributions of the interception plot could increase as soil water content augments, which was observed by Ghahramani and Ishikawa (2013). Second, spatial heterogeneity could remain high despite the large size of the plots, due to differences in micro-surface, depressions, soil depth layers and plant distribution (Saison et al., 2008). And third, the model considers water dynamics in only one soil layer. But, the water dynamics in the upper layer may depend sometimes on water logging that comes upward from deeper layers. Thus, to simulate such dynamics would require much more complex modeling, such as applying Richards' equation (Richards, 1931) to different layers.

5.3 Influence of coffee management practices on runoff and erosion

Treatment effects in general were not very evident in terms of superficial runoff, sediment concentration and soil loss due to highly variable results. High variations were expected since this is common in soil erosion studies, especially when working with low values, as Nearing et al. (1999) observed from results reported around the world. High soil erosion rates were expected, which would have controlled for variability; however, this was not the case, and low soil loss rates per rainfall events were common.

Treatment selection was based on potential practices producers could adopt without compromising their production tradition, thus any change suggested based on these results would be easy to promote.

The experimental design of treatment application had one particularity, the no mini-terraces renewal obliged to apply the practice in the other six plots. Although it was done to mimic the real practices in the fields, it clearly decreased our analyzing power. The experience was that the effect of this renewal was stronger than expected. We hope that, as the effect will lessen and get more stable in the future, next years of data will allow to produce data that will better show the differences between treatments. However, the ratios estimation helped to remove the rainfall effect in the given year.

The no mini-terraces renewal had a significant runoff increase just after the renewal. The sediment concentration and soil loss decreased significantly ($P<0.05$) the year after when soil moisture was below 30%, but soil loss had a significant increase when soil moisture was above 35%. These effects are the scenario that producer would have if terraces renewal is not performed periodically, but based on our results of three years, it is not possible to determine yet the best recommended periodicity for mini terraces renewal.

Chemical weed control was expected to lead to higher runoff and soil loss due to vegetative material loss for longer time than mechanical control that recovers faster. There was no significant change in any of the three dependent variables measured. Some possible reason for this could be: 1- the herbicide effect could be detected maybe after more than two years of records. 2- it could be necessary a rainier year with less or none effect of previous dry years effect on low soil storage status in order to collect higher runoff records and detect easier any effect. 3- the influence of soil litter was good enough for soil protection to rainfall impact and runoff speed up. 4- the high variability associated did not allow capturing any difference. And last, 5- there is no significant effect of herbicide exclusive control on soil erosion in the study conditions.

The reduced pruning pressure (leaving more branches on the shade trees) was expected to produce higher canopy coverage and more vegetative material the year after the treatment initiated since once the treatment started actually less branches were cut and left on the ground, but more canopy accumulated for next year. At the same time more evapotranspiration was expected from shade trees, then a drier soil condition could happen and higher soil infiltration capacity. From those changes less runoff production was expected. The reduced pruning significantly ($P<0.04$) reduced runoff in transition period and the year after. Also, there was a significant ($P<0.04$) decrease in runoff, sediment concentration and soil loss the year after of treatment application. These results, the strongest among the three treatments, could reinforce the hypothesis for the positive expected effect. One negative expected consequence of this canopy increase over the coffee plantation was an increase of diseases such as "ojo de gallo" (*Mycena citricolor*). However it did not happen under those plots until 2013.

In general, no mini-terrace renewal seems to lose the opportunity of erosion reduction after a year of application if the practice is done just before the rainy peak moment. Weed control with only herbicide did not show a significant effect on superficial runoff nor soil loss. Reduced pruning pressure seems to be a potential practice in order to reduce superficial runoff and soil loss, being careful with potential incidence of diseases due to excess trees shade.

5.4 Runoff and erosion processes at the scale of a small watershed dominated by coffee fields on steep slope

The dynamic of runoff at both scales changed according to rainy season time. It seems the same dynamic observed at plot scale between rainfall and soil moisture status could affect the watershed response to rainfall. In 2012, from July (time of flume installation) the watershed runoff was higher than plot runoff. Once the rainy peak approached in 2012, the runoff (in mm) from plot tended to be greater than the watershed records. The same pattern was present in 2013, on a rainy season with more rainfall events, but this time the difference between both scales were more evident. Rainfall event above 40 mm produced a runoff difference between both scales even larger. A possible explanation for this change in trends as soil profile got wetter is the possibility that at watershed scale, the superficial soil layer did not saturate easy due to better soil infiltration perhaps or deeper soil profile with more water storage capacity and minimum soil infiltration rate was not reached many times. At the same time, at plot scale this soil profile water saturation was reached faster than watershed. In complement to this possibility, the scarce riparian vegetation in the two sides of the main stream could work as strip barriers to runoff and sediments.

The runoff contribution from roads where the fluxes usually concentrate could make an important contribution to the runoff measured at watershed scale. It was not measured in site. Gómes-Delgado (2010) assumed that runoff from roads was the main contributor to watershed runoff since the measured runoff from two large plots was much lower than runoff at watershed scale (Andisols in Aquiares, Turrialba, Costa Rica). The infiltration rates of a volcanic soil as in the watershed where Gómes-Delgado worked could be easily higher than in Ultisols. Thus, the roads contribution in runoff to our watershed should be lower than reported for Aquiares site. In our study assuming roads runoff coefficient of 65% (Rijsdijk et al. 2007) or 80% (Ziegler et al. 2004) gave overestimation of runoff from roads captured in the watershed outlet. Another potential source of high runoff production in the watershed could be gullies areas, which covered a small area in the watershed. As a complementary point in here, dirt roads (without gravel) had weeds along the tracks and borders, which could work as runoff barriers. However, this was out of the scope of this work. It was not possible to measure their runoff contribution.

Sediment concentration in general was higher at plot scale (per rainfall event) compared to watershed records at flume control. However under high rainfall events, at watershed scale sediment concentration increase between 2-3 times magnitudes compared to plot average after rainfall event. The difference in here is the measuring detail of sediment concentration; at flume site it was continuous every 10 min, but at plot scale it was the result of average sediment concentration of whole runoff collected (if rainfall produce less than 40 L per plot) or a sample of heavy rains runoff production. Once the average sediment concentration (diluted or weighted by total discharge) registered per rainfall event at flume was estimated, the value got smaller than plots. However, high sediment concentration records were observed (up to 9 g l^{-1}) in the flume and they would be ignored if averages for whole event were used instead. It is very likely that the same sediment concentration dynamic observed at flume point with at least one peak also occurred at plot scale. Therefore, the average sediment concentration estimated from plot could underestimate total soil loss. The rainfall events chosen to analyze the dynamics at both scales simultaneously were large in discharge. They had similar peak pattern in runoff with an expected faster response from plots since the evident concentration time differences.

During the onset of the rainy seasons or after long periods of no rainfall events, it seems the sediment came mostly from the riverbed. Once the rainy season approached to the end (September and October) where soil got wetter, the sediments seems to come from further areas of the watershed and not only from riverbed. This could be determined base on the time difference in runoff peak (equivalent to discharge peak) with respect to sediment concentration peak. This lagging or leading differences could help to understand where sediments were coming from mainly. The first, lagging, runoff peak occurred first and followed by sediment concentration peak meaning sediment from around the watershed. The leading is the contrary, first sediment concentrate peak and then runoff peak thus the sediments came from riverbed. These results mean the potential soil erosion moment occurred on soil wetter periods and soil must be protected against this condition. The weed control could be done after this critical period and terraces renewal if apply for that year should also wait until this period is over.

5.5 Implications for runoff and erosion control and watershed management

The dynamic between rainfall and soil moisture played a key role in soil erosion at the study site. It was demonstrated that October is the critical time where these two factors combined caused extreme runoff and soil loss production. Despite the weather variability due to ENOS phenomena some years (2012 and 2013 in this study) and the unexpected rainfall pattern, October still was a critical month. Practices such as weed control, shade tree pruning and mini-terraces renewal should not be made in this period. Beginning of rainy season could be a proper moment or end of rainy season when rainfall events are scattered.

The mini-terraces renewal could have a good reduction in runoff and sediment concentration in the long run (> 1 year) after stabilization on coverage and risers. Another advantage of this structure is making harvesting easier.

The mechanical weed control at watershed has the advantage of no water contamination into the soil profile and aquifer. However the required effect of soil clearance for long time prior harvesting was reached better by herbicide application. This chemical control would be preferred after rainy season peak.

5.6 Conclusion and perspectives

This shade coffee systems under steep slope seems to be more stable environmentally in terms of soil erosion than expected and an overestimation of sediment contribution from this AFS could happen as reported by Solano (2010) applying RUSLE equation and collecting sediments (silt fence mesh) from coffee plots located in the South sector of the Pirrís watershed.

The assessment of runoff and soil loss on a plot scale under a coffee plantation on a steep slope showed that the mean annual erosion rate under these conditions was about 1 t ha^{-1} yr^{-1}. This moderate value is related to the low and relatively constant sediment concentration (about 1.3 ± 0.3 g/l), whereas the surface runoff rate showed a strong seasonal pattern with low values. The good soil coverage observed throughout the rainy season plus the presence of old mini- terraces contributed to efficiently decreasing the erosion rate. Good soil coverage also explain why we measured erosion rates consistently lower than reported by other authors on coffee crops (Vahrson and Cervantes, 1991; Thomaz, 2009; Solano, 2010) working on bare soil, where cultivation practices and low aggregate stability produced soil crusting.

Shade coffee systems evaluated in this study, not just a plot scale but also at watershed scale, demonstrated how soil coverage disturbance and canopy reduction on shade trees had an evident effect on runoff and sediment concentration. Soil loss was estimated at both scales from those two variables. The dynamic between sediment concentration and runoff varied since a high runoff production (even at watershed scale) not always matched with high sediment concentration, thus different combinations between these two variables could result and affect soil loss.

The doubt concerning roads runoff contribution was also present in other studies and still is a question. A potential approach for answering this question would be to measure that contribution in site.

In terms of results variability, it would be really important to consider more plots replicates, at least 3, but more than that would be better definitely.

The low presence of buffer strips observed in the riparian zone was thin as a first sight (corroborated from aerial image). This riparian zone should be increased giving potential benefits of runoff reduction before it reaches the mainstream flow. A better management of superficial runoff by ditches throughout the watershed in combination with vegetative barrier would also reduce runoff and soil, but needs to be evaluate at least at plot scale (and at least 3 replicates)

The more effective treatment on runoff and soil loss reduction was reduced pruning pressure. However the two years observed could be a short time to determine if that extra shade is counterproductive causing an increase in diseases. This doubt could let to continue measuring this pruning practice more years and also testing different pruning pressures (5, 6, 7, … branches left on the tree). It should be checked that same quantity and distribution of shade trees are present in all plots. In order to build a strong database, a specific control on leaf area index for shade trees would be preferred every 2-3 weeks.

Finally, the high sensibility of the studied coffee system to soil coverage disturbance and canopy reduction measured in our experiment, with regard to runoff and soil loss, suggest that this system is potentially highly vulnerable and may produce more erosion in case of degradation of any of the vegetal surface protection layer.

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Annex A. Tipping bucket calibration

All eight tipping buckets were calibrating individually. The water flow was adjusted from 0.1475 l min^{-1} up to 19.64 l min^{-1} by adjusting manually the control valve inlet water flow.

The water flow source was from a container of 20 gals approximately located 1.5 m above the tipping level. A flexible tube was used for connecting the water source container and the tipping and a control flow valve was located in the tube. The water level on the container source was constant by filling it from a pipe water source, whereas the maximum water flow possible.

Once a constant flow was determined, that rates was maintained from 7 min up to 24 min when readings seems to be constant, but when the water flow rate was very low (<1 l min-1) the recording was prolonged for 1 and the most stabilized continuous records were selected. All the reading impulses from the tipping buckets were recorded into a CR1000 Datalogger.

Analyzing the data it was observed a quadratic trend of the data for every tipping bucket records. A linear fit was evaluated but the R2 was always lower than the one from a quadratic regression.

Table A.1. Calibration of 8 tipping buckets (1 l capacity per tip) used on runoff plots. San Isidro, San Pablo de León Cortés, San José, Costa Rica. $Y= a X + b X^2$ where Y is estimated liters flow and X is tipping number registered in the datalogger.

Tipping #	X	X^2	n	R^2 adjusted
1	0.93389	0.01627	11	0.889
	(0.02823)	*(.00220)*		
2	0.98642	0.00863	7	0.800
	(0.00384)	*(0.00032)*		
3	0.93143	0.01574	24	0.954
	(0.02215)	*(0.00165)*		
4	0.99065	0.01204	24	0.954
	(0.00765)	*(0.00057)*		
5	0.97224	0.00480	21	0.947
	(0.01044)	*(0.00072)*		
6	1.08148	0.00472	24	0.954
	(0.00924)	*(0.00072)*		
7	1.05128	0.00310	21	0.947
	(0.00874)	*(0.00063)*		
8	1.03761	0.00597	21	0.947
	(0.00745)	*(0.00052)*		
1-8	1.02087	0.00704	153	0.992
	(0.01427)	*(0.00105)*		

Note: all the coefficients are significant prob. > 0.001.
Standard errors in parenthesis.

Annex B. Diskin and Nazimov infiltration model

Model structure

The infiltration model has two elements (Fig. B.1). One is an inlet regulating element, denoted as *f(t*), which regulates the water that comes from rainfall, *R(t)*. If the precipitation rate is higher than the superficial soil layer infiltration capacity rate, *q(t)*, then this difference becomes runoff, *y(t)*, also called excess rainfall; otherwise the infiltration rate equals the rainfall rate and it is also called the actual or real infiltration rate. This second component is a storage element given by the same superficial soil layer that regulates how much of the infiltrated water percolates (*g(t)*) based on soil water storage conditions, *S(t)*, which are dynamic. When maximum soil water storage from the second element (S_m) is reached, the minimum infiltration rate, *fc* takes place. If the storage element is depleted, then the maximum infiltration rate, *fo*, is assumed. This fluctuation in soil water storage from the superficial soil layer (or constrained on the infiltration soil layer) is the mechanism that links both elements. Also, both elements are linked by the output of the first element, which becomes the input for the second element.

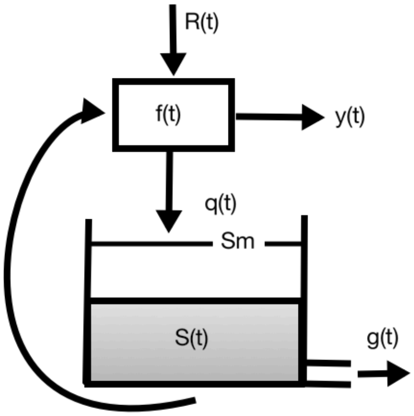

Figure B.1. Schematic representation of the two-component structure of infiltration model (modified from Diskin and Nazimov, 1995).

Input variables:

The infiltration model uses the following input variables:

Ri: Rainfall intensity in mm per hour estimated from 5 min lapse records; this was therefore the lapse time used for other variable estimations too.

S: Soil water storage in the superficial soil layer, which is assumed to be a linear reservoir in the sense the output was proportional to the storage volume. Units are in mm of water depth. This variable is required just before the rainfall event starts as an initial soil water content point. The fluctuations in this variable depend on rainfall intensity, the maximum storage capacity of the superficial soil layer, and the infiltration capacity rate.

Model parameters:

The model has three parameters but only the first two mentioned below were found by optimization whereas the third one was estimated from field data. Fig. A.2 gives a clear relationship between the minimum soil infiltration capacity rate and the maximum rate too when soil water storage from the superficial soil layer changes during rainfall and infiltration lapses over a rainfall event.

f_c: Minimum infiltration capacity rate when the soil water content of the upper soil layer is at its maximum value, hence the smallest infiltration rate possible.

f_o: Initial infiltration capacity rate when the soil water content of the upper soil layer is completely depleted, hence maximum infiltration capacity.

S_m: maximum value of soil water storage in the upper soil layer.

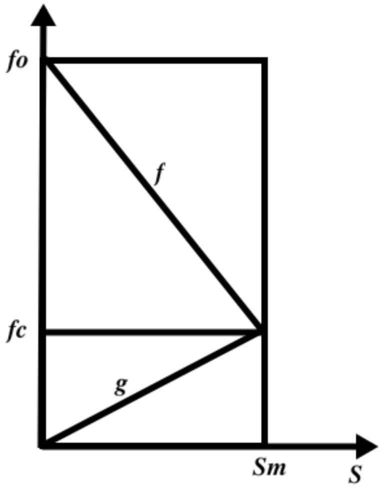

Figure B.2. Schematic representation of the Diskin and Nazimov model of maximum soil layer infiltration capacity and percolation as the superficial soil layer water storage changes, where the minimum soil layer infiltration capacity is constant. (Modified from Diskin and Nazimov, 1995).

Calibration strategy:

The rainfall recording frequency was 5 min, which was considered short enough not to need an estimation of the initial and final infiltration rates. Therefore, only the final infiltration and precipitation rate for each 5 min lapse were used.

The total runoff depth per rainfall event (excess rainfall) estimated by the model was compared with observed runoff (27 extreme selected rainfall events). Fourteen of the selected 27 rainfall events were used for calibration and they were selected randomly. Once optimum values were found for *fc* and *fo,* close values were tested in order to guarantee that the local maximum found was the best optimization combination point. The remaining 13 events were used for validation. Optimum f_c and f_o values were determined by minimization of the summation of all the absolute differences between observed and estimated runoff per rainfall event. The optimization method was GRG (non-linear generalized reduce gradient) and boundary infiltration rates were imposed for f_c and f_o (5-40 mm h^{-1} and 40-150 mm h^{-1} respectively).

Annex C. Runoff, sediment concentration and soil loss summary from 2011 to 2013 per treatment at plot scale.

Table C.1. Monthly summary for reference treatment (Ref) for period 2011-2013. Llano Bonito, San Pablo de León Cortés, Pirrís watershed, Costa Rica.

Variable	Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual^{+}
Total runoff depth (mm)	*2011*	-	-	1.90	6.81	7.14	53.8	4.66	**74**
		-	-	*(0.19)*	*(0.08)*	*(0.55)*	*(9.76)*	*(2.40)*	*(10)*
	2012	0.38	0.55	0.72	7.29	4.49	22.8	1.53	**38**
		(0.04)	(0.05)	(0.09)	(2.13)	(0.84)	(4.09)	(0.85)	(5)
	2013	0.34	0.96	0.29	1.05	4.00	17.9	0.64	**25**
		(0.12)	(0.19)	(0.07)	(0.08)	(0.27)	(5.26)	*(0.12)*	*(5.3)*
Sediment concentration (g l^{-1})	*2011*	-	-	1.49	0.87	1.40	1.50	1.02	**1.45**
		-	-	*(0.12)*	*(0.06)*	*(0.16)*	*(0.08)*	*(0.09)*	*(0.44)*
	2012	1.08	1.98	1.24	1.47	1.27	1.91	1.37	**1.47**
		(0.07)	*(0.28)*	*(0.06)*	*(0.21)*	*(0.05)*	*(0.09)*	*(0.21)*	(0.40)
	2013	1.31	1.66	1.37	1.08	1.35	1.61	0.84	**1.31**
		(0.36)	*(0.20)*	*(0.04)*	*(0.05)*	*(0.09)*	*(0.18)*	*(0.15)*	*(0.69)*
Total soil loss (kg ha^{-1})	*2011*	-	-	45.1	40.5	110	1316^{bl}	107	**1620**
		-	-	*(11.8)*	*(1.97)*	*(17.2)*	*(254)*	*(12)*	*(238)*
	2012	4.48	9.17	9.71	134	126^{bl}	488	12.0	**784**
		(0.71)	*(2.72)*	*(1.05)*	*(59.8)*	*(22.3)*	*(113)*	*(6.92)*	(133)
	2013	*3.52*	*22.3*	*3.90*	*11.7*	*61.8*	404^{bl}	*6.44*	**514**
		(1.53)	*(13.3)*	*(1.00)*	*(0.70)*	*(2.62)*	*(44.4)*	*(1.16)*	*(64)*

Standard deviation in brackets; bl: it indicates bedload accumulated in plots collectors is added.

Table C.2. Monthly summary for no mini terraces renewal treatment (NT) for period 2011-2013. Llano Bonito, San Pablo de León Cortés, Pirris watershed, Costa Rica.

Variable	Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual^{+}
Total runoff depth (mm)	*2011*	-	-	5.67	11.3	13.0	97.7	5.70	**139**
		-	-	*(3.61)*	*(7.78)*	*(5.85)*	*(84.1)*	*(4.26)*	*(54)*
	2012	0.43	0.61	1.35	12.2	7.95	29.7	1.61	**54**
		(0.10)	(0.10)	(0.40)	(1.15)	(0.52)	(7.61)	(0.69)	(33)
	2013	0.36	0.70	0.46	1.69	6.98	21.3	1.21	**33**
		(0.40)	(0.38)	(0.20)	(0.34)	(4.12)	(10.1)	*(0.16)*	*(7.4)*
Sediment concentration (g l^{-1})	*2011*	-	-	1.83	1.01	0.98	1.40	1.09	**1.26**
		-	-	*(0.78)*	*(0.36)*	*(0.44)*	*(0.09)*	*(0.03)*	*(0.31)*
	2012	1.03	1.73	1.89	1.62	1.11	1.23	1.37	**1.43**
		(0.05)	*(0.12)*	*(0.16)*	*(0.09)*	*(0.06)*	*(0.06)*	*(0.14)*	(0.28)
	2013	0.96	1.11	1.09	1.11	1.27	1.82	0.62	**1.14**
		(0.09)	*(0.04)*	*(0.08)*	*(0.12)*	*(0.08)*	*(0.19)*	*(0.08)*	*(0.28)*
Total soil loss (kg ha^{-1})	*2011*	-	-	124	123	156	1371^{bl}	131	**1904**
		-	-	*(34.5)*	*(69.4)*	*(20.8)*	*(1191)*	*(94.7)*	*(535)*
	2012	5.33	11.1	15.4	223	167^{bl}	486	6.70	**914**
		(0.99)	*(3.32)*	*(8.66)*	*(27.1)*	*(15.1)*	*(140)*	*(0.56)*	(159)
	2013	*2.48*	*11.0*	*7.44*	*15.7*	*114*	420^{bl}	*4.56*	**575**
		(1.36)	*(4.33)*	*(1.89)*	*(1.96)*	*(16.6)*	*(140)*	*(0.63)*	*(156)*

Standard deviation in brackets; bl: it indicates bedload accumulated in plots collectors is added.

Table C.3. Monthly summary for herbicide treatment (H) for period 2011-2013. Llano Bonito, San Pablo de León Cortés, Pirris watershed, Costa Rica.

Variable	Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual^{+}
Total runoff depth (mm)	*2011*	-	-	2.87	4.09	9.04	41.4	3.54	**65**
		-	-	*(0.15)*	*(0.93)*	*(1.87)*	*(2.52)*	*(0.97)*	*(2.6)*
	2012	0.23	0.41	0.58	6.68	4.73	13.0	1.01	**27**
		(0.05)	(0.05)	(0.12)	(1.35)	(0.81)	(1.27)	(0.11)	(2.0)
	2013	0.44	0.55	0.27	0.89	4.57	12.9	0.76	**20**
		(0.16)	(0.22)	(0.03)	(0.16)	(0.20)	(0.58)	*(0.11)*	*(0.7)*
Sediment concentration (g l^{-1})	*2011*	-	-	1.28	0.81	1.29	1.25	0.81	**1.09**
		-	-	*(0.12)*	*(0.07)*	*(0.15)*	*(0.11)*	*(0.08)*	*(0.20)*
	2012	0.73	0.94	0.92	1.53	1.17	1.61	1.48	**1.20**
		(0.09)	*(0.12)*	*(0.07)*	*(0.12)*	*(0.18)*	*(0.16)*	*(0.26)*	(0.40)
	2013	0.53	0.38	0.70	0.74	1.14	1.21	0.30	**0.71**
		(0.04)	*(0.08)*	*(0.14)*	*(0.11)*	*(0.10)*	*(0.13)*	*(0.04)*	*(0.30)*
Total soil loss (kg ha^{-1})	*2011*	-	-	54.6	40.7	119	718^{bl}	70.0	**1003**
		-	-	*(12.3)*	*(21.0)*	*(7.43)*	*(173)*	*(16.6)*	*(176)*
	2012	1.40	3.48	4.82	120	104^{bl}	299	15.2	**548**
		(0.34)	*(0.98)*	*(1.72)*	*(47.7)*	*(34.0)*	*(88.1)*	*(7.47)*	(108)
	2013	*2.42*	*3.27*	*1.53*	*7.89*	*51.9*	*250*^{bl}	*3.74*	**321**
		(0.93)	*(2.35)*	*(0.68)*	*(2.80)*	*(8.07)*	*(49.2)*	*(0.38)*	*(84)*

Standard deviation in brackets; bl: it indicates bedload accumulated in plots collectors is added.

Table C.4. Monthly summary for reduce pruning treatment (RP) for period 2011-2013. Llano Bonito, San Pablo de León Cortés, Pirris watershed, Costa Rica.

Variable	Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual^{+}
Total runoff depth (mm)	*2011*	-	-	4.18	6.27	12.0	74.5	5.99	**108**
		-	-	*(0.45)*	*(0.18)*	*(3.92)*	*(0.69)*	*(0.02)*	*(4.0)*
	2012	0.27	0.83	0.88	7.68	5.38	17.1	1.61	**34**
		(0.06)	(0.23)	(0.30)	(0.36)	(0.36)	(1.40)	(0.16)	(1.5)
	2013	0.14	0.62	0.30	1.00	3.86	11.7	0.57	**18**
		(0.03)	(0.19)	(0.04)	(0.14)	(0.19)	(0.32)	*(0.05)*	*(0.4)*
Sediment concentration (g l^{-1})	*2011*	-	-	1.70	1.06	1.61	1.88	1.29	**1.51**
		-	-	*(0.17)*	*(0.16)*	*(0.16)*	*(0.21)*	*(0.21)*	*(0.45)*
	2012	1.42	1.29	1.59	1.95	1.60	2.16	1.06	**1.58**
		(0.24)	*(0.11)*	*(0.11)*	*(0.11)*	*(0.13)*	*(0.24)*	*(0.30)*	(0.52)
	2013	1.32	0.87	1.00	1.00	1.09	1.18	0.50	**0.99**
		(0.33)	*(0.07)*	*(0.15)*	*(0.19)*	*(0.10)*	*(0.13)*	*(0.07)*	*(0.50)*
Total soil loss (kg ha^{-1})	*2011*	-	-	94.7	85.6	252	1031^{bl}	81.3	**1545**
		-	-	*(31.7)*	*(63.4)*	*(4.60)*	*(261)*	*(4.7)*	*(68)*
	2012	4.06	13.1	16.0	174	140^{bl}	564	26.6	**937**
		(1.71)	*(2.28)*	*(6.81)*	*(14.8)*	*(14.3)*	*(90.4)*	*(14.8)*	(94)
	2013	*1.38*	*7.02*	*4.07*	*11.3*	*40.8*	*229*^{bl}	*3.67*	**297**
		(0.49)	*(4.06)*	*(1.90)*	*(4.59)*	*(6.03)*	*(68.2)*	*(0.76)*	*(69)*

Standard deviation in brackets; bl: it indicates bedload accumulated in plots collectors is added.