**Sensitivity of the landslide model LAPSUS\_LS to vegetation and soil parameters**

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# Abstract

The influence of vegetation on slope stability is well understood at the slope level but scaling up to the catchment level is still a challenge, partially because of a lack of suitable data to validate models. We tested the physical landslide model, LAPSUS\_LS, which models slope stability at the catchment scale. LAPSUS\_LS combines a hydrological model with a Limit Equilibrium Method model, and calculates the factor of safety of individual cells based on their hydrological and geomorphological characteristics. We tested two types of vegetation on slope stability: (i) coffee monoculture (*Coffea arabica*) and (ii) a mixed plantation of coffee and deep rooting Erythrina (*Erythrina poeppigiana*) trees. Using soil and root data from Costa Rica, we performed simulations to test the response of LAPSUS\_LS to root reinforcement, soil bulk density, transmissivity, internal friction angle and depth of shear plane. Furthermore, we modified the model to include biomass surcharge effect in the calculations. Results show that LAPSUS\_LS was most sensitive to changes in additional cohesion from roots. When the depth of the shear plane was fixed at 1.0 m, slopes were not unstable. However, when the shear plane was fixed to 1.5 m, the mixed plantation of coffee and trees stabilized slopes, but the coffee monoculture was highly unstable, because root reinforcement was low at a depth of 1.5 m. Soil transmissivity had a limited impact on the results compared to bulk density and internal friction angle. Biomass surcharge did not have any significant effect on the simulations. In conclusion, LAPSUS\_LS responded well to the soil and vegetation input data, and is a suitable candidate for modeling the stability of vegetated slopes at the catchment level.

**Keywords:** modeling, cohesion, roots, soil, transmissivity, bulk density, slope stability

# Introduction

Landslides are now among the most widespread natural hazards in the world (Stokes et al. 2013; Bogaard and Greco 2015). On vegetated slopes, land use change is known to have a major effect on slope stability. Several studies have shown that a switch from forest to crops increases landslide frequency (e.g. Glade 2002, Kumar et al. 2007). Therefore, the development of a model that can simulate the effect of land use changes on slope stability at the catchment level would be of central importance for decision makers to plan effective land use change strategies in mountainous regions.

Different types of models have been formulated over the years to predict landslide risk (see Stokes et al. 2009). A widely used approach is the Limit Equilibrium Method (LEM), where an estimation of the Factor of Safety (FoS) is based on physical data of soil and vegetation properties, such as transmissivity, soil cohesion and additional cohesion from roots (Greenwood 2005; Stokes et al, 2008; Mao et al 2013). However, previous studies have generally focused on the calculation of FoS at the slope level, to understand why a slope has failed locally. Upscaling slope stability models to the catchment level is still a challenge, partially because of a lack of suitable data to validate models, the challenge of selecting realistic input data in a heterogeneous environment, and also because of a lack of understanding of biophysical processes at different scales. Therefore, it is necessary to investigate the upscaling problem using different approaches. We suggest identifying a physical landslide model that calculates slope stability at the catchment level, and to test its sensitivity to vegetation and soil parameters. Parallel studies should focus on investigating how soil hydrological and physical processes at the slope level are altered over a larger scale and vice versa (Bogaard and Greco 2015).

We tested the physical landslide model, LAPSUS\_LS (Claessens, 2005), to investigate the influence of vegetation on slope stability at the catchment scale. In previous studies using LAPSUS\_LS (Claessens 2005, 2006, 2007; Keijsers et al. 2011), the influence of vegetation (in the form of additional cohesion from plant roots, Cr) was included as a parameter but not investigated in detail. More specifically, it was performed a back analysis of landslides in a given catchment and the cr value was adapted for different vegetation classes to match the observed landslides, but without direct measurements of root density and tensile strength.

We chose to test LAPSUS\_LS because of its ease of use, the relatively small amount of data required, the possibility to include spatial heterogeneity of data and the use of a standard FoS equation, thus making the model a suitable choice to examine the effect of vegetation on slope stability at catchment scale. Therefore, we performed simulations to investigate two specific aspects:

i) Determine the influence of vegetation parameters (in particular root reinforcement and vegetation surcharge) on the model output in a catchment with two different types of land use.

ii) Estimate the influence of soil properties (depth of shear surface, bulk density, internal friction angle, soil cohesion and transmissivity) on the model output, with regard to the two types of land use.

Simulations were performed using vegetation and soil data obtained from previous studies (Meylan et al. 2012, 2013; Villatoro et al. 2015; Nespolous, 2011; Prieto et al. 2015)conducted in the area and results are discussed with regard to the model’s sensitivity to these parameters.

# Materials and Methods

## Overview of the model LAPSUS\_LS

LAPSUS\_LS combines a hydrological model in the form of water balance with a Limit Equilibrium Method (LEM) model, calculating the factor of safety (FoS) of each cell based on its hydrological and geomorphological characteristics. With the aid of GIS maps it is possible to provide different input values to different areas of the catchment, depending on land use. LAPSUS\_LS is based on the calculation of the critical rainfall (Qcr) for slope instability, which is the amount of water needed to trigger a landslide in a 10x10m given cell. Calculation of Qcr is based on a steady state hydrological model in combination with a deterministic infinite slope stability model to delineate areas prone to landsliding due to surface topographical effects on the hydrological response (Montgomery and Dietrich, 1994; Pack et al., 1998). In an infinite slope stability model, the stability of the slope is characterized by the FoS, defined as the ratio between the available shear strength (stabilizing force) and the shear stress (destabilizing force) (Claessens, 2005). A full overview of LAPSUS\_LS is given in the Supplementary Materials.

The outputs of the LAPSUS\_LS model are: (1) a map of landslide risk classified according to the minimum steady state rainfall needed to trigger landslides, (2) a map of eroded material in the catchment and deposition of material (e.g. Figure 1) and (3) the total amount of soil displaced by landslides and the amount of soil deposited inside the catchment. The difference between these two values represents the soil displaced outside the catchment.

## Study area and modeling scenarios

To determine the sensitivity of LAPSUS\_LS to various vegetation parameters at the catchment scale, soil and vegetation data were analyzed from a site in Costa Rica. The area selected for the study was Llano Bonito, a catchment of 18 km2 in the region of Terrazù/Los Santos. The area has a humid tropical climate with two different seasons: a dry season from December to April, with little rainfall, and a rainy season from May to November (Villatoro et al. 2015). According to Villatoro et al. (2015), a weather station located 4 km away, in Carrizales De Leon Cortes, registered an average year rainfall of 2444±409 mm for the period 1990-2006. The average altitude ranges between 1150 and 2200 ma.s.l. The geological formation belongs to the Terraba schist of Miocene age. The soils are ultisols with a high content of clay and iron (Soil Survey Staff, 2010).

An extensive cultivation of coffee (*Coffea arabica*) of the dwarf *caturra* variety is grown in the area (Meylan, 2012). Coffee is cultivated either in a monoculture or in association with shade-inducing trees, e.g., Erythrina (*Erythrina poppigenea*) or a variety from the banana family (*Musa spp*.). The area is characterized by steep slopes, with up to the 80% of the coffee in the area cultivated on these slopes (Meylan et al. 2013). This type of cultivation makes the area prone to erosion, especially to mass movements. Different densities of shade trees and coffee plants are used, with an average of 7470 ± 626 coffee plants per ha and 598 ±126 Erythrina trees per ha (Villatoro et al. 2015).

To understand the influence of vegetation parameters when using LAPSUS\_LS, two scenarios were compared. (i) coffee monoculture (hereafter termed ‘*coffee’*), and (ii) coffee and Erythrina(hereafter termed ‘*coffee + trees’*) grown together in association.

## Data collection for scenarios

Soil data were collected from previous studies implemented in the area. Transmissivity values were taken from Meylan (2012) and soil cohesion, bulk density and friction angle from Nespoulous (2011). The number of roots crossing a given surface area of soil was derived from Prieto et al. (2015). Root tensile strength was estimated using a generic equation (e.g. Genet et al. 2005; Kuriakose, 2010; Mao etal.2012; Mao et al. 2012,):

Where Trn is the tensile strength for the n root and dn the diameter of the n root; and are coefficients specific for every species. These factors were also used by Mao et al. (2012 and 2014). According to Mao et al. (2012), the α and β coefficients do not differ significantly between tree and shrub species. In our study, two general coefficients for tree roots from Genet et al. (2005) were used. In Genet et al (2005), the root tensile strength approximated with the equation [2] resulted in acceptable values of additional cohesion by roots and were used in slope stability models (Genet et al. 2005; Mao et al 2012, 2014). The equation using coefficients from Genet et al. (2005) was (Table 1):

[2]

These data were used to calculate the additional cohesion from roots (cr) according to the Wu and Waldron model with a correction factor (Preti, 2006), which avoids overestimation of cr (Wu, 1976; Waldron, 1977; Wu et al. 1979). To calculate the biomass surcharge for the different land uses, dendrometric equations from the work of Gene et al. (2005) (for Erythrina) and Suarez et al. (2002) (for coffee) were used. The results obtained gives a biomass surcharge of 9.09 N/m2 for coffee and 126.81 N/m2 for coffee + trees land uses, respectively.

## Modeling approach

To investigate the suitability of LAPSUS\_LS to model landslide catchment processes and the influence of vegetation, it was decided to use input data from field studies. Using real data will help our understanding of the adjustment and calibration that the model needs after a ground truth studies or after selecting input data from the literature. For example, the soil cohesion factor (cs) in this study was determined for a soil with its water content close to that found in the field during the sampling period, which was 7-20% below the field capacity. However, the LAPSUS\_LS model was developed to work with cohesion levels determined at soil saturation (Claessens, 2005). Pellet et al. (2013) and Ghosh (2012) state that clay soils in particular experience a drop in cs at soil saturation. Previous studies using LAPSUS\_LS reported post-calibration levels of up to 50% increase in cs (Keijsers et al. 2011). The bias given by the water content of soil also influenced the internal friction angle values. The values calculated by Nespoulous (2011) (see Table [1]) were high compared with the values found in the literature for saturated clay soils in Costa Rica (from 20° to 43°; Hulgade Herra, 2006). Given the uncertainty of soil cohesion, and of other soil input data, we performed simulations to test the sensitivity to the different parameters at decreasing levels of cs, to mimic the effect of soil water saturation on soil properties. Simulations were performed varying the following parameters to test the sensitivity of the model: additional cohesion from roots (cr, in equation [S2], Supplementary Materials); transmissivity (T in equation [S4], Supplementary Materials), internal friction angle (ϕ in equation [S4] [S5], Supplementary Materials) and bulk density ( in equations [3] in discussion and [S4] [S5] in Supplementary Materials). The sensitivity analysis was carried out by varying the collected input data (Table 1) by ±10% intervals. The values were increased until reaching a +100% of the original value and decreased until reaching the 0% values, to plot the sensitivity of the model to the different input data. The model was than modified to include biomass surcharge in the calculation of critical rainfall values (modification of equations [S4], [S5] and [S6], see Supplementary Materials). Several runs were performed for different cs and cr values including the influence of biomass surcharge. The results of the model with and without biomass surcharge were compared to understand its influence on the LAPSUS\_LS simulations.

# Results

## Sensitivity of LAPSUS\_LS to vegetation parameters

When *coffee + trees* was tested and the shear surface was fixed at a depth of 1.0 m, landslide activity started when soil cohesion cs reached 20 % of its initial value (5.38 kPa) and soil additional cohesion cr was low or null (≤20 %) (Figure 2 A). When cs was zero, landslides started to occur at cr≤50 % (Figure2 A). When the shear plane was fixed at a depth of 1.5 m, the landslide risk increased compared to when the shear plane was at 1.0 m depth (Figure 2 B). With a completely non-cohesive soil (cs= 0 %), cohesion added by roots cr was not enough to keep the catchment in a stable situation, and landslides occurred even with 100 % cr (Figure 2 B). It is interesting to notice that when the shear plane was fixed at either depths of 1.0 m or 1.5 m, the cs data were the same, but the initial cr was greater when the shear plane was at 1.5 m (27.48 kPa) compared to 1.0 m (14.48 kPa). However, the soil displaced by landslide events increased when the shear plane was at a depth of 1.5 m depth, because of the higher soil load on the shear surface. On a steep slope, the higher load means a higher tangent force on the soil, increasing the risk of landslide initiation. In the *coffee* only scenario, landside events started when cs = 10.78 kPa (40 % of initial cs) with no cr from roots (cr= 0 %). With a cs of 5.38 kPa (20 % of initial cs), landslide events started with a cr equal to 50 % of the initial value (Figure 2 B); the catchment was thus highly instable when cs= 0 kPa.

When the shear plane depth was fixed at a depth of 1.0 m, the catchment was stable when cs> 60 % and cr> 50 % (Figure 2 C). The amount of soil displaced by landslide increased with decreasing cs, and when soil was completely non-cohesive, a low cr (cr≤ 40 %) resulted in landslides in the catchment (Figure 2 C). When the shear plane was fixed at a depth of 1.5 m (Figure 2 D), the catchment was only stable when cs>60 % and cr> 80 %.When cs was <40 % (5.01 kPa), cr was not sufficient to keep the catchment stable, resulting in high landslide activity (Figure 2 D). The drop of cs to 5.01 kPa is physically acceptable assuming complete soil saturation (Pelletet al. 2013; Ghosh, 2012).

Regarding the effect of implementing biomass surcharge in the model, for coffee + trees the difference in soil displaced with and without biomass surcharge was almost negligible (-2.1 %, i.e. 213 m3 less soil from a total of 10900 m3). For the coffee plantation, the addition of surcharge increased slope stability by only -0.1 %, due to the low biomass of plants (Figure S3, Supplementary Materials).

## Sensitivity of LAPSUS\_LS to soil parameters

When simulations were performed to determine the effects of bulk density it was necessary to define a range of possible bulk density values in a realistic situation. Low bulk density values can be found in andosols, and according to Wijaya et al. (2004) the range can be from 0.49 to 0.66 gcm-3. Rawls (1982) studied 2721 soil horizons and found a peak value of bulk density of 2.09 gcm-3. This range of values corresponds approximately to 40 % and 150 % of the bulk density values used in this study (Table 1, Figure 3).

In both vegetation scenarios (all vegetation parameters were the same), decreasing bulk density led to increased amounts of soil displaced by landslides (Figure 3), until bulk density reached a threshold where amounts of soil began to decrease, i.e. the trend reversed. This threshold value depends on the initial values of cs; the lower the cs, the lower the threshold value. Therefore, it is necessary to investigate the validity of the model below this threshold, and it is important to understand the influence considering possible future uses of the model.

When the sensitivity of the LAPSUS\_LS was examined with regard to transmissivity, in the *coffee* monoculture, when cs and cr were both fixed at 100%, no soil displacement was detected regardless of the variation in soil transmissivity. When cs fixed at 40% of the initial value determined on the field (5 kPa), an increase in transmissivity decreased the displacement of soil (Figure S2 Supplementary Materials). Decreasing the transmissivity by 90% resulted in an increase of soil displaced by landslides of +22%. Doubled transmissivity values resulted in a decrease of -59% of displaced material.

Regarding the internal ϕ, it plays an important role in the output of the model, (Figure S3). A decrease of the internal friction angle results in an increase of soil displaced by landslides, especially when soil cohesion values are low. When soil cohesion is equal to 40% of the initial value, passing from ϕ≅46.5° to ϕ≅14.3° can produce an increase of displaced soil in the catchment equal to 600% (Figure S3).

# Discussion

LAPSUS\_LS was sensitive to differences in both vegetation and soil parameters, but the differences observed in the two land uses depended on the initial input data. The soil cohesion values (Nespoulous 2011) were relatively high in comparison to existing literature (Claessens et al. 2005, 2006, 2007; De Sy et al. 2013; Keijsers et al. 2011), because direct shear tests were performed at a wetness index 7 - 20 % lower than field capacity. These data resulted in an overestimation of cs since LAPSUS\_LS was developed to work with cohesion levels measured at soil saturation (Claessens et al., 2007). This is particularly true for clay soils that can experience the higher drop in cohesion due to water saturation (Pellet et al. 2013, Ghosh 2012). The use of dry instead of wet bulk density may also affect results. Comparing wet and dry bulk density, Campbell (1973) found an average increase of 19.5 % in the latter. Our results show that an increase in bulk density would result in a lower volume of sediment displaced. However, another effect of a higher bulk density is a decrease of the total cohesion C value (Eq. [S2] Supplementary Materials), which would result in a greater risk of landslides. More research is needed to understand the balance between the two opposing effects. We used data from direct shear tests performed at unsaturated conditions (Nespoulous 2011) and thus both cs and ϕangle were high. Lower values of ϕ caused increased soil displacement in the catchment (Figure S3), therefore the level of water content in the soil is an essential factor to be considered when a field survey is performed. Our results show that: 1) soil input data need to be typical of those during a landslide event (e.g. when soil is close to saturation) and 2) calibration of input values is needed for a valid performance of the model (Claessens et al. 2005, 2006, 2007; Keijsers et al. 2011;).

## Sensitivity of LAPSUS\_LS to vegetation parameters

When the shear plane was fixed to a depth of 1.0 m, few differences were found in slope stability between coffee and coffee + tree plantations. Coffee + tree plantations started failing at low cs (<20%) whereas in the coffee plantations, a much higher cs was needed to trigger a landslide (e.g. cs=60% and cr=0 or cs=40% and cr=10%).

This result is due to the lower initial cs of coffee (12.5 kPa) compared to coffee + tree (26.9 kPa). However, the low cs of coffee was compensated by its high cr (40.2 kPa) at a depth of 1.0 m. This phenomenon made the catchment with a *coffee* monoculture stable under these conditions, since to trigger landslides, a severe drop of both soil and root cohesion is needed.

Landslides increased significantly in the *coffee* plantation when the shear plane was fixed at a depth of 1.5 m. The catchment was highly unstable when cs was < 60 % of its initial value. Contrary to other scenarios, maximum cr was not sufficient to prevent landslides, because of the low initial cr (3.8 kPa) of *coffee* at a depth of 1.5 m. Therefore, if the shear plane occurred at 1.5 m during slope failure, coffee monocultures would result in a very unstable catchment compared to *coffee + tree* plantations. These results suggest therefore that deep rooting tree species would be useful for improving slope stability in coffee monocultures.

Our simulations stressed the importance of the shear plane depth. Landslide risk and soil displacement was consistently higher when the potential shear plane was deeper in the soil, due to the greater weight of soil on the shear surface. On steep slopes, the tangent force related with soil weight increases thus decreasing slope stability. This phenomenon is reflected in the model behavior: with the same soil cohesion even the catchment showed a higher risk of slope failure when the shear plane was set at a depth of 1.5 m compared to when it was set at 1.0 m. When soil weight on the shear surface increased (equation [S2] Supplementary Materials), the overall C value was decreased, which subsequently decreased the critical rainfall value of a cell (equation [S4] Supplementary Materials), inducing slope failure to occur earlier. These results underline the importance of selecting a realistic shear plane depth for the catchment. Another factor not easily accounted for in the simulations is variation in soil depth: LAPSUS\_LS simulates failure using a uniform soil depth over the entire slope, but soil depth is usually heterogeneous along a slope (Crozier and Preston,1999; Brooks et al. 2002; De Sy et al. 2013). Therefore, future work should enable a more heterogeneous slope to be modeled with regard to soil depth.

In conclusion, *coffee* and *coffee + tree* were both stable when the shear surface was at a depth of 1.0 m, since only small areas of instability on the slope occurred. The *coffee* plantation had a particularly high cr at a depth of 1.0 m, but was highly unstable at a depth of 1.5m due to the low cs and cr. The presence of Erythrina improved slope stability when the shear surface was fixed at 1.5 m, because these species are deep-rooting. However, when grown in conjunction with *coffee*, the cr of *coffee* was much lower at a depth of 1.0 m, compared to that in the *coffee + tree* plantation, possibly due to competition between the root systems of the two species.

The implementation of the biomass surcharge in the model leads to a slight overall increase of slope stability in the catchment (Figure S3 Supplementary Materials), as previously observed (e.g. Hammond et al. 1992). However, the model assumes an evenly distributed biomass surcharge throughout the catchment (Hammond et al. 1992), but the surcharge of trees has different effects depending on where the tree is placed spatially in a plot (Gene et al. 2005). The contribution of surcharge results in smaller differences of soil displaced during a landslide than the modification of the model, thus making predictions unreliable. Therefore, we propose that it is not necessary implement vegetation surcharge in LAPSUS\_LS.

## Sensitivity of LAPSUS\_LS to soil parameters

The sensitivity of LAPSUS\_LS to soil cohesion involved only the modification of the cs parameter in equation [S2] (Supplementary Materials), which in turn defines the critical rain fall values required to cause a landslide. This parameter is of central importance for the calculation of the amount of soil displaced by landslides, also because the value of cs is used to calculate the depth of soil displaced by landslides (equation below, see Supplementary Materials for a complete overview):

[3]

However, the value of cs in the calculation of the amount of soil Sn (equation [3]) was fixed (10kPa) in the simulations. Therefore, the differences in the amount of soil displaced were only due to the increased number of cells affected. If the reduction of cs had been implemented in equation [3] the effect would have been enhanced. Equation [3] is inversely proportional to soil cohesion, meaning that a reduction of 50 % of cs would result in twice the amount of sediment displaced. However, the cs factor needs to be estimated and calibrated from empirical data and observations to correctly predict landslides (Claessens et al. 2007; Keijsers et al. 2011). Calibration on observed landslides should therefore be conducted to efficiently select the cs factor in equation [3].

Soil bulk density had a major impact on the amount of soil displaced by landslides (Figure 3). A small decrease in bulk density increased sediment displacement significantly. This behavior is due to higher saturated water content, which causes a low bulk density, and subsequently increases susceptibility to erosion (Roberts et al. 1998; Jepsen et al, 1997). The same process affects landslides, where a lower bulk density allows more water to infiltrate in the soil, increasing the pore pressure and decreasing the cohesiveness of the soil shear layer (Crozier, 1999). Several authors have shown that the presence of trees reduces bulk density, especially in shallow soils, due to mulching and higher root presence (Messing et al. 1997; Mishra et al. 2003; Fisher, 1995; Soeabi et al. 2005). However, the lower bulk density for *coffee + trees* at a depth of 1.5 m did not significantly alter slope stability in our study. In the *coffee* plantation, bulk density was higher at a depth of 1.5 m but did not prevent the triggering of landslides. This result was due to the low cs and cr that made the slope unstable despite the higher bulk density. Therefore, cs and cr are more important parameters for managers to consider calibrating, when aiming at improving slope stability.

LAPSUS\_LS calculated that for values below a certain threshold, lowering bulk density decreased landslide erosion, rather than increasing it (Figure 3). Therefore, a theoretical weakness may exist in the model leading to an inaccurate prediction of the amount of soil displaced by landslides. This behavior suggests caution using the model below a certain bulk density threshold. A possible explanation for the drop in displaced material by landslide above a certain bulk density value can be found in the part of the model that deals with the trajectory of failed slope material. To calculate the depth of the failed slope, the model uses an equation [3] based on the work of Johnson and Rodine (1984).

The bulk density multiplied the entire factor in the numerator of equation [3], so according to equation [3] lowering the bulk density resulted in a smaller depth of material displaced for each cell. However, with a decreased bulk density the model increasing soil displacement due to landslides (Figure 3). This phenomenon is due to two factors: i) with a lower bulk density, the model decreased the critical rainfall value of each cell (Equation [S4] Supplementary Materials) and ii) with a lower bulk density the model decreased the number of cells that became unconditionally stable (equation [S5] Supplementary Materials). In this way, the decrease of bulk density increased the number of cells that result in a landslide. Since the effect of bulk density on equation [3] is lower than that caused when a higher number of cells fail (equation [S4] and [S5] Supplementary Materials), the overall volume of soil displaced increased. However, the model reached a threshold when all the cells that could be ‘unstable,’ due to a lowering of bulk density, were triggered. After this threshold the number of unstable cells does not change anymore but the depth of displaced material kept decreasing due to the effect of bulk density values on equation [3]. This result could lead to the decrease of the overall amount of soil displaced in the catchment below a certain threshold of bulk density.

With regard to soil transmissivity, the relationship between transmissivity and soil displaced by landslides was non-linear: the variation of values of soil displacement due to increased transmissivity was higher than the variation due to decreased transmissivity. The model predicted greater soil displacement due to landslides with lower transmissivity, and more stable slopes with higher transmissivity values. The reason for this behavior is in the wetness index used by the LAPSUS-LS model. The FoS equation used by the model has a wetness factor W that is substituted according to a steady state hydrological response model based on O’Loughlin (1986) and Moore at al. (1988). If the soil has a low transmissivity value (impermeable or thin layer of soil) W will augment, increasing the amount of water logging in the soil. Higher soil moisture content therefore increases the probability of triggering a landslide (Borga et al. 1998).

# Conclusion

The LAPSUS\_LS model was sensitive to the vegetation parameters tested, in particular additional cohesion from roots. As vegetation characteristics are highly heterogeneous in a catchment, coupling LAPSUS\_LS with a model that can predict vegetation heterogeneity (especially root heterogeneity) could greatly improve the performance of the model. We also showed that the effect of surcharge from vegetation is negligible; therefore it is not necessary to include this parameter in LAPSUS\_LS.

The reliability of LAPSUS\_LS is dependent on how carefully the input data are selected. Therefore, to model the influence of vegetation it is fundamental to select reliable soil input data. The heterogeneity of a catchment, the biases of the procedures used to produce data and the simplifications needed, make selecting reliable input data a challenging task. For example, deriving soil characteristics at an appropriate water content (i.e. a fully saturated soil), is necessary for the most important soil input data: bulk density, soil cohesion and internal friction angle. Soil depth was one of the fundamental factors driving the results of the model: to correctly use LAPSUS\_LS, it is important to select a known or realistic depth of potential shear plane. We also suggest running the model for different shear plane depths to understand the influence of vegetation in the catchment.

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Table 1: Input values used for the different runs with LAPSUS\_LS model. The first two columns refer to the *coffee* monoculture land uses with the shear plane fixed to depths of 100 and 150 cm. The second two columns refer to *coffee + Erythrina* with the shear plane fixed to depths of 100 and 150 cm. Data are for unsaturated soil (see text for details). The data for root cohesion are calculated with the Wu and Waldron method, with Preti correction factor (Preti, 2006)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** |  | **unit of measure** | **coffee monoculture 100 cm** | **coffee monoculture 150 cm** | **coffee + trees 100 cm** | **coffee + trees 150 cm** |
| **Root additional cohesion** | **cr (WWM)** | [kPa] | 40,21 | 3,76 | 14,48 | 27,48 |
| **Soil cohesion** | **cs** | [kPa] | 12,51 | 12,51 | 26,94 | 26,94 |
| **Total cohesion** | **C** | [-] | 4,13 | 0,83 | 3,22 | 2,92 |
| **Shear plane depth** | **h** | [m] | 1 | 1,5 | 1 | 1,5 |
| **Soil bulk density** | **ρs** | [g/cm3] | 1,3 | 1,36 | 1,31 | 1,27 |
| **Transmissivity** | **T** | [m2/d] | 8,37 | 12,55 | 10,66 | 16,01 |
| **Internal friction angle** | **ϕ** | [°] | 48,96 | 48,96 | 45,92 | 45,92 |

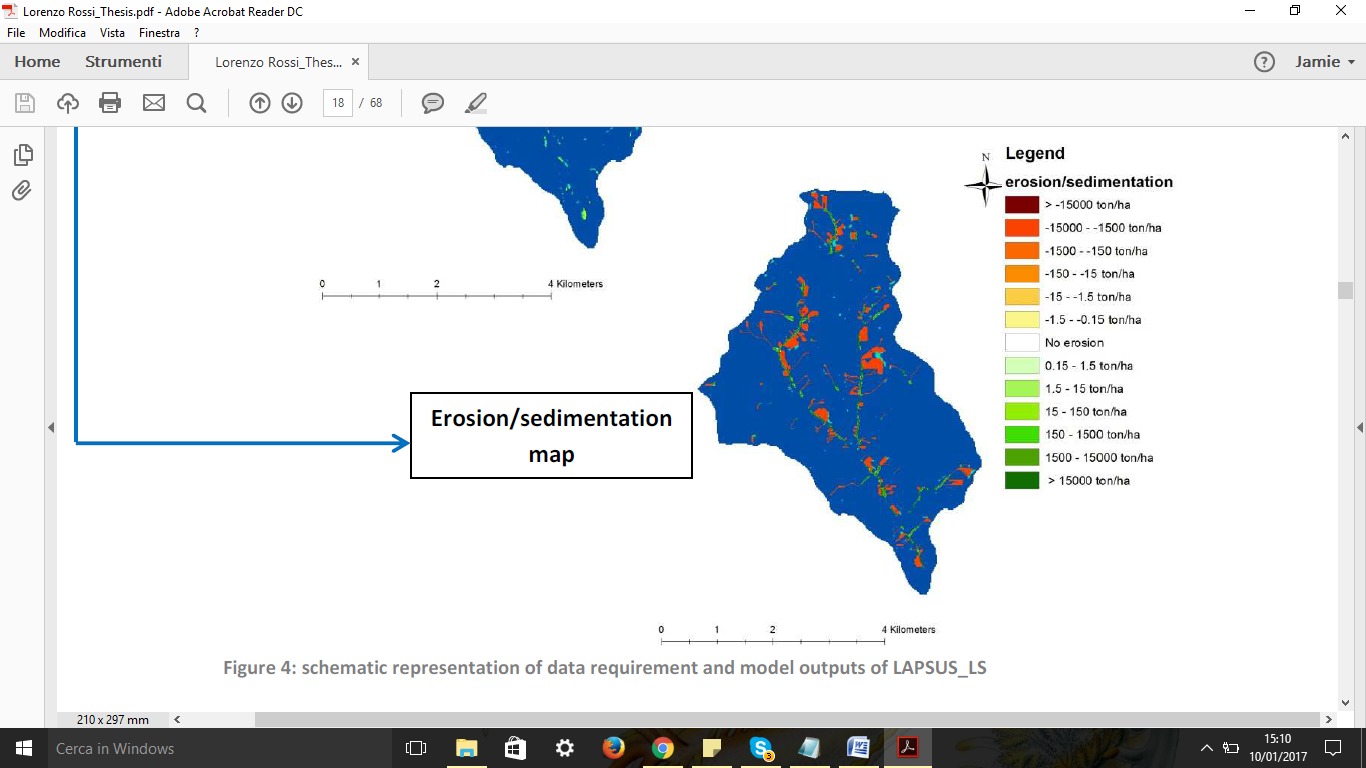


Figure 1: Example of an erosion/sedimentation map derived from LAPSUS\_LS for the region of Llano Bonito, Costa Rica. The map represents a catchment with an area of 18 km². The red/yellow colors represent the cells where landslides displacement took place and the different values of soil displaced by the event, while the green cells represent the deposition fans and the amount of soil displaced in that cell.

**B – Coffee + trees**

Shear plane 150 cm

**A – Coffee + trees**

Shear plane 100 cm

**Volume of soil displaced by landslides (m3)**

**D – Coffee**

Shear plane 150 cm

**C – Coffee**

Shear plane 100 cm

**Additional cohesion from roots (cr) expressed as a % of the original value**

Figure 2: Results of the simulations performed for different root additional cohesion values (cr %). The cr is expressed in percentage of the original one (see table 1). The simulations were performed for different soil cohesion values, represented by the different lines (cs). The sol cohesion is again calculated as a percentage of the measured one (see table 1). The four scenarios are A) *coffee + trees* with the shear plane depth set at 100 cm, B) *coffee + trees* with shear plane depth at 150 cm, C) *coffee* monoculture with shear plane depth at 100 cm and D) *coffee* monoculture with shear plane depth set at 150 cm.

Figure 3: Sensitivity analysis to bulk density. The simulations were conducted for the coffee monoculture with the shear plane fixed to a depth of 150 cm. Different values for soil cohesion were tested (cs 100% - 60% 40%). The white area within the dashed lines represents the range of realistic bulk density values.