Original scientific paper

Impacts of Forest Roads on Soil in a Timber Harvesting Area in Northwestern Mexico (a Case Study)

Ciro Hernández-Díaz, Jesús Soto-Cervantes, Javier Corral-Rivas, Eusebio Montiel-Antuna, Ramón Alvarado, Rodolfo Goche-Télles

Abstract

The impacts of forest roads on soil were studied in a timber harvesting area of 92 ha in the municipality of San Dimas, state of Durango, Mexico. The area included 3127 m of main roads, 2907 m of secondary roads and 2979 m of tertiary roads. The timber was harvested at the beginning of 2012. After logging, soil loss by run-off during the rainy season was assessed along the truck ruts. This variable was correlated with the width and the longitudinal and transverse slopes of the road. The overall average road density (98 m/ha) indicated an average external yarding distance of 102 m. This is a short distance considering that timber was drawn with a jammer, which can pull logs over a distance of 300 m or more. Run-off in the rainy season decreased the ground level by between 38 and 58 mm along the truck ruts, and the soil loss was different in each type of road. The findings have led us to propose the elimination of some tertiary roads, to reduce the total road density to 78 m/ha. This is more than sufficient for logging, especially if the jammer capacity is improved, e.g., by applying the highlead system or the aerial yarding system with jammer. We estimate that soil loss would be reduced by 20% with the proposed changes to the road network. Additionally, the new road network would enable almost 20% of the area now occupied by roads to be reforested.

Keywords: yarding systems, road density, run-off, erosion

1. Introduction

Rural roads are essential for the social and economic development of communities in mountainous or semi desert locations, where access to basic health services and education is very complicated (Mills 1997). These roads enable people to study, enjoy and live within wild areas and forests, and they facilitate leverage of resources and ecosystem services (Keller and Sherar 2004, Tolosana et al. 2000, Bruce et al. 2011, Deegen et al. 2011).

Forest roads also have major environmental impacts. Building forest roads involves removal of vegetation and soil, thus favoring run-off, pollution of streams, and the risk of erosion (Keller and Sherar 2004, Naghdi 2004). The ecosystem also becomes fragmented and weakened, wildlife habitats are altered (Gucinski 2012), and anthropogenic activities that further increase the impacts on ecosystem impacts are generally favored (Dykstra and Heinrich 1996, Keller and Sherar 2004, FAO 2008).

The impacts may be minimal if the roads are designed and managed carefully, with the aim of protecting nature (Demir 2007). Therefore, the available equipment, machinery and technology should be optimally used to harvest wood products in the cutting areas, in order to build and maintain only those roads that are actually required (Hernández 1993).

Building forest roads is expensive, particularly in sites with steep topography and the presence of rock. Investment is only made in constructing forest roads when the cost can be justified. However, the justification is usually based solely on financial issues or short term social interest, and sufficient attention is not given to the potential environmental impacts, which may

Fig. 1 Jammer with one reel, which is the type commonly used in timber harvesting operations in Mexico

reverse the balance of the initially perceived benefits in the medium and long term (López 2009).

In Mexico, timber harvesting requires efficient planning (López 2009) and also improved planning and design of forest roads (Daniluk 2002). In general, timber harvesting operations should not be analyzed separately, but following comprehensive, integrated plans (Hernández 1993). In addition, logging roads should be designed and laid out by competent engineers, who are aware of the need to minimize soil disturbance, to establish proper drainage systems and avoid crossing watercourses (Dykstra and Heinrich 1996, Álvarez et al. 2010, Tenerife 2011, Naghdi 2004).

One of the main parameters for evaluating a road network is its density, which indicates the length of road per unit area (Keller and Sherar 2004). In Europe, the average density of forest roads for ground skidding is about 25 m per hectare of forest (Dykstra and Heinrich 1996).

The machine most commonly used for timber harvesting in Mexico is the jammer »motogrúa« (Mendoza 1997) (Fig. 1). This is a timber yarding machine that is usually equipped with just one cable winch, used to directly pull one log at a time (direct pulling system). The average external yarding distance with this system is almost never longer than 150 m, which implies an average road density >65 m/ha.

Use of a two drum jammer would enable application of the highlead yarding system and the skyline yarding system with jammer. The latter has already been successfully tested in Mexico, showing that it is possible to yard logs from distances of 400 m or more (Hernández et al. 2002), whereby the density of roads required could be reduced to around 25 m/ha, as in Europe.

The skyline yarding system with jammer can also be applied in areas where the highlead system is appropriate; it requires minimal additional investment and training and would reduce the density of roads needed in various harvesting areas by more than half (Hernández et al. 2002).

Owners and managers of timber harvesting companies should train operators and make maximum use of the available technology and capacity and reaching range of equipment and machines for log yarding (Dykstra and Heinrich 1997). This would reduce the need for roads, reducing environmental impacts and also increasing the area available for the production of trees and biodiversity conservation.

The objectives of this study were to evaluate some impacts on soil of the existing network of roads in a cutting area that was harvested in 2012 and to compare these with the impacts associated with the proposed road network.

2. Materials and methods

2.1 Location

The study was conducted in a property known as La Trinidad (Lots Four and Five of Fraction ll), where timber was harvested in 2012 (Fig. 2). The site is located between latitude 24°18′06″ and 24°17′35″ North and longitude 105°49′00″ and 105°47′28″ West, in the municipality of San Dimas, Durango, Mexico. The elevation in the area ranges from 2200 to 2800 meters above sea level.

2.2 Methods

With the aid of a GPS navigator, the coordinates of the study area were plotted on a map, and the area in which timber harvesting had recently been carried out was calculated. Before the rainy season in 2012, the study area was inspected to establish the location of the roads and trails, to measure them and to plot them on a map of known scale. The contour lines were then added to the map (equidistance, 20 m) along with the slope and the current yarding distance, and also the

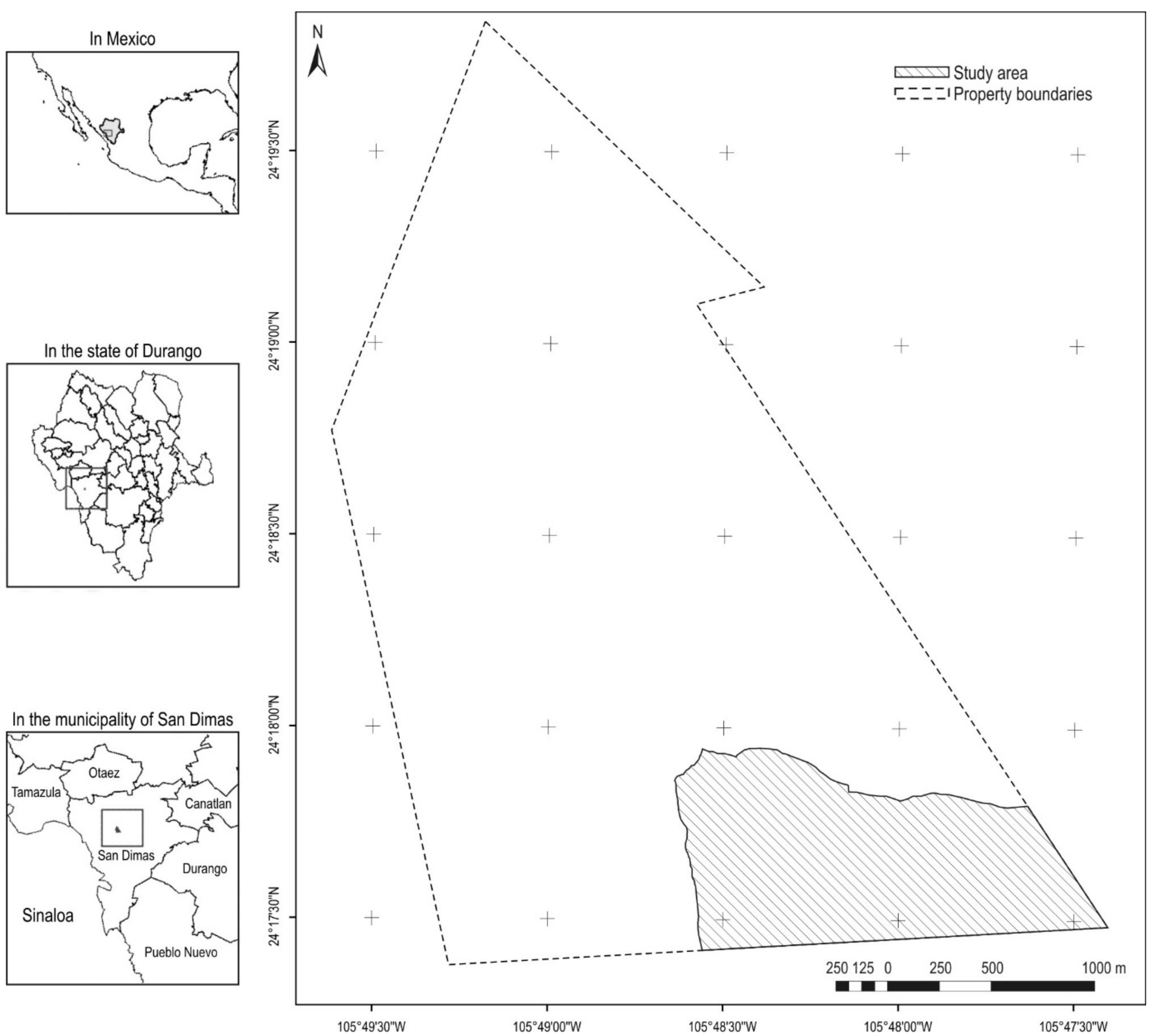

Fig. 2 Maps showing the location of the study area

proposed distance for harvesting the logs, assuming that the yarding equipment was used to full capacity for the type of terrain.

In the roads under study, sections were marked every 50 m as possible sites for sampling points for placing stakes to enable measurement of erosion. Thirty-one (31) sampling points (50% of the possible points) were positioned on the main road, which is 3127 m long. The positions of all sampling points along the road were randomly selected, using the following system. Strips of paper were marked with numbers from 1 to 62 and placed in a bag. Paper strips (31) were removed from the bag at random, and the number on each paper was multiplied by 50 to establish the distance, in meters, from the initial reference point of intersection of the main road, for the location of each sample.

The same procedure was followed for selecting the position of sampling sites in secondary and tertiary roads. In Mexico, tertiary roads (brechas) are the simplest and cheapest but also the lowest quality roads used for timber harvesting; these roads do not have bridges, culverts, ditches or bed liners.

At each sampling point, a wooden stake was stuck as far as possible into the ground in the middle of the rolled tracks: it was assumed that vehicles would no longer pass along the road because timber harvesting was completed in that area. The stakes were used to mark and compare the level of the ground at the beginning and the end of the rainy season, to enable estimation of the amount of soil lost by run-off along the truck tracks. The width, gradient and cross slope of the road were also measured at each sampling point. These data were used to estimate the area devoid of vegetation for each type of road and also to evaluate the possible effect of the slope on the magnitude of soil loss due to run-off. Soil loss per area equivalent to one hectare covered by truck tracks in each type of road, was estimated as follows:

$$SL = \left(lb - la\right) \times 10.000 \tag{1}$$

Where:

- SL soil loss in the truck tracks, m^3/ha;
- $(lb - la)$ difference in soil level measured before and after the rainy season, m.

Density and average external yarding distance were also estimated (assuming that yarding with jammer is always done from the bottom upwards in the direction of the slope):

$$RD = \frac{RL}{A} \tag{2}$$

$$AEYD = \frac{10.000}{RD} \tag{3}$$

Where:

- RD road density, m/ha;
- RL total length of the road of interest in the cutting area, m;
- A cutting area, ha;
- $AEYD$ average external yarding distance, m.

The exposed surface without vegetation per hectare was calculated as follows:

$$EA = RD \times Aw \tag{4}$$

Where:

- EA area exposed by the type of road, m^2/ha;
- RD density of the same kind of road, m/ha;
- Aw average width of the road, m.

2.3 Statistical analysis

Nonparametric tests were used, as the data did not meet the basic conditions required for application of regression analysis. The Spearman's correlation coefficient (r_s), which indicates the degree of relationship that may exist between two variables, was calculated and expressed as follows (Mora 2008):

$$r_s = 1 - \left(6\sum_{1}^{n} di^2\right) / \left(n\left(n^2 - 1\right)\right) \tag{5}$$

Where:

- r_s magnitude of the correlation between the two variables, which can be direct (+) or indirect (–) and can acquire absolute values between zero and unity;
- di^2 squared differences between each observation range of the two variables, when the observations are ordered with respect to each variable;
- n number of observations in the sample.

Furthermore, the non-parametric Kruskal Wallis test, also known as the H Test (Acuña 2013), was used to determine whether the magnitude of soil loss by runoff was the same for the three types of roads. This test enables comparison of independent samples and does not require that the data conform to a normal or any other distribution; it is based on comparison of the medians of the samples using the H statistic, expressed as follows:

$$H = \frac{12}{N\left(N+1\right)}\left[\sum\frac{R_1^2}{n_1} + \sum\frac{R_2^2}{n_2} + \sum\frac{R_3^2}{n_3}\right] - 3\left(N+1\right) \tag{6}$$

Where:

H test statistic;

R_1, R_2, R_3 ranges for each observation of each sample, obtained when considering together all observations in the three samples compared;

n_1, n_2, n_3 the size (number of observations) of each sample;

N the sum of all the observations in the three samples.

3. Results and discussion

The logging area under study covers 92 ha and includes 3127 m of main roads, 2907 m of secondary roads and 2979 m of tertiary roads. The average road density is 98 m/ha, which is equivalent to an average external yarding distance of 102 m from the road. This is considered a very short distance given the capacity and the potential reach of the jammer.

3.1 Yarding distance and current density of roads

In some parts of the cutting area, the roads were separated by distances of more than 250 m and sometimes even more than 300 m. In these sites, it was not possible to pull up the logs with the jammer using the traditional system of »direct pull« with a single cable, as the maximum average range with this system is 150 m.

Comparison of the current road density (98 m/ha) with the technically feasible density for jammer, suggested as 33 m/ha or less (Dykstra and Heinrich 1996, Hernández et al. 2002) shows that the road density in the cutting area exceeds the cited parameter by three times. This may lead to negative environmental impacts such as loss of vegetation, reduced water infiltration and increased soil compaction, runoff, habitat fragmentation and pollution of streams and water bodies (Akbarimehr and Naghdi 2012, Grace and Clinton 2007).

3.2 Soil loss by run-off from the road

The average values of parameters measured in random samples from each type of road are shown in Table 1. The decrease in the ground level corresponds to the difference in level at the beginning and the end of the rainy season in 2012. The width of each road was measured considering the area devoid of vegetation due to the passage of the road. This was measured from the start of the ravine on one side of the road to the area where soil removal was noticeable on the other side of the road. We noted that the road was wider in many areas due to truck tracks. The longitudinal and transverse slopes were measured from the center of the road at each sampling point.

Table 1 Estimated average values of each variable, in relation to types of road

Variable	Main roads ($n_1 = 13$)	Secondary roads ($n_2 = 24$)	Tertiary roads ($n_3 = 10$)
Reduction of ground level, cm	5.8	4.1	3.8
Soil loss, m^3/ha	580	410	380
Road width, m	4.5	5.0	4.5
Track total width, m	1.6	1.4	1.2
Longitudinal slope of road, %	12.9	10.5	6.2
Hillside slope, %	22.5	22.5	11.1

According to data recorded at the weather station closest to the study area (located at a distance of 40 km, La Victoria, San Dimas, Durango), the precipitation level between June and October 2012 was 620.4 mm. Run-off and sediment delivery to water streams have been shown to be proportional to the amount and distribution of annual precipitation (Kahklen 2001), although confirmation of this is beyond the scope of this study.

3.3 Statistical analysis

The values of the Spearman's correlation coefficient (r_s) for the relationship between the soil loss in each road type and the variables evaluated are shown in Table 2. When the correlations were significant (e.g. hillside slope on main roads [r_s = 0.83]), it was concluded that the observed effects are not due to chance and that these variables are possible causes of soil loss.

Analysis of the data classified by road type revealed significant correlations in only three cases, particularly in secondary roads, for which slightly more

Table 2 Spearman's coefficients (r_s) for correlations between soil loss and the variables evaluated. The values shown in bold type indicate significant correlations ($p<0.05$)

Road type	Road width, m	Hillside slope, %	Road longitudinal slope, %
Main road (n_1=13)	ns	0.83	ns
Secondary road (n_2=24)	0.48	ns	0.66
Tertiary road (n_3=10)	ns	ns	ns
All roads (N=47)	0.69	0.63	0.50

ns – not significant ($p<0.05$).

observations (24) were made (Table 2). In relation to the tertiary roads, for which fewer observations were made, no significant relationship between soil loss and any of the explanatory variables was detected. However, when the data were analyzed together for all the three types of roads (last row), the three coefficients were found to be moderately significant. The relationship between soil loss and each of the three variables considered may have been clearer if larger samples had been available for each type of road.

3.4 Comparison of soil loss in relation to type of road

The results of the Kruskal Wallis test indicate significant differences in soil loss between the three types of roads analyzed ($p<0.05$), as the calculated H value (375,792) was much higher than the tabulated H value (6221). This is consistent with the results of the Spearman test. It also confirms that the analyzed variables have an effect on the magnitude of soil loss on forest roads and that the magnitude differs depending on the characteristics of the road.

3.5 Proposals regarding yarding distance and road density

The primary and secondary roads are planned to reach places outside the cutting area, and be used also for other purposes besides harvesting timber; therefore, proposals for amending these roads are beyond the scope of this study. However, on the basis of the results and the observed density of roads inside the study area, we suggest closing 1827 m of tertiary roads inside the cutting area, which would reduce road density from 98 m/ha to 78 m/ha. These roads represent 20% of the existing roads and their closure would significantly reduce the number and magnitude of environmental impacts.

The proposed closure of some tertiary roads relies on the assumption that by leaving only the main and secondary roads, the yarding distance would not be greater than 300 m. This distance is achievable with the jammer if used with the highlead system, especially if it is supported with other methods like using animals (horses or oxen) to pre pull the logs toward the jammer lane in moderately sloping areas.

Another option is to apply the skyline yarding system with jammer, mentioned in the introduction. In this system, installation of the jammer in each workstation is slightly more complicated and time consuming than with the direct pull system. However, given that it extends the yarding distance by two or three times, a much larger area is drained from each road with the skyline system, which involves extraction of a larger volume of wood at each station. The use of this system also reduces the necessary effort by workers and risks involved. Since fewer roads are required, larger areas will be covered by vegetation, including timber trees, and runoff and the overall environmental impact will be reduced (Hernández and Alcázar 2003).

3.6 Soil loss associated with the proposed road network

Table 3 shows the estimated soil loss for each road type in the study area. The proposal involves closure of only some of the tertiary roads, and therefore the estimated soil loss is only reduced in this type of road.

With the current length of tertiary roads (2979 m), soil loss is approximately 135.8 m^3, and it is estimated that reduction of this type of road to only 1152 m would reduce soil loss to 52.5 m^3, which indicates a reduction of 61.3% in soil loss in the rainy season associated with this type of road. It is also estimated that if only the primary and secondary roads were left, and by closing some of the tertiary roads, the total soil loss would be

Table 3 Estimated changes in soil parameters associated with the proposed changes to the road network in the study area

Road type	Road length, m	Track width, m	Reduction of ground level, cm	* Total soil lost within both tracks, m^3	** Estimated soil loss due to tracks, m^3/ha
Main road	3127	1.6	5.8	290.2	580.0
Secondary road	2907	1.4	4.1	166.9	410.0
Tertiary road	1152	1.2	3.8	52.5	380.0
Average	–	1.5	4.8	–	479.2
Total	7186	–	–	509.6	–

* Total amount of soil actually lost within both tracks along each road type

** Estimated soil loss per hectare of track area (not forest area)

Table 4 Area devoid of vegetation with the current road network and with the proposed network

Road type	Current road network			Proposed road network		
	Length, m	Road width, m	Area devoid of vegetation, m^2	Length, m	Road width, m	Area devoid of vegetation, m^2
Main road	3127	4.5	14,071	3127	4.5	14,071
Secondary road	2907	5.0	14,535	2907	5.0	14,535
Tertiary road	2979	4.5	13,405	1152	4.5	5184
Total	9013	14	42,011	7186	14	33,790

509.6 m^3 rather than the 592.9 m^3 currently lost in the rainy season; in other words, the global soil loss in the truck tracks would be reduced by more than 14%, due to the reduction in the density of forest roads.

3.7 Bare soil area due to roads

Table 4 shows the area devoid of vegetation due to the presence of roads in the current network and the corresponding area after closure of the roads and reforestation of the sites. An area of 8221 m^2 could be returned to forest production, which represents a reduction of 19.6% of area that is devoid of vegetation due to the presence of roads. This is important in relation to both the increased timber production and also the reduction in environmental impacts associated with deforestation.

The use of two drum jammers (one drum for the mainline and the other for the haulback line), like the ones used in Durango before 1975, yields a substantial improvement enabling a reduction in the area occupied by tertiary roads.

This machine could be used to apply the skyline yarding system with jammer and to harvest the logs from a distance of 400 m or more. It is also possible to pull logs from an average distance of 300 m (equivalent to an average road density of 33 m/ha) by only applying the highlead yarding system, which was used about 100 years ago when the jammer was initially brought to Mexico. Any of these two systems, with this road density, would enable harvesting all of the trees in that cutting area, which could not be reached with the current yarding system (direct pulling) given the current road network.

We recommend that future studies should use more sampling points for measuring the variables analyzed in this paper. Other independent variables that could contribute to explaining the magnitude of soil loss on forest roads should also be studied: a) degree of soil compaction, b) presence of ditches, culverts and other roadworks, c) type of soil covering the road bed, d) intensity and frequency of rainfall, and e) the quantity and weight of trucks using the road, among others. Medium and long-term studies should also be conducted to evaluate the effect of the intensity of annual precipitation. Finally, observations should also be made in several different timber harvesting areas, to enable comparisons and possible extrapolation of the results.

4. Conclusions

The width and the longitudinal and transverse slopes of the roads affect soil loss by run-off via truck ruts. Although the unitary loss is different for each type of road, the overall loss increases with the number and length of roads in forestry areas. Here, we propose closing of some tertiary roads to decrease the total density of roads in the cutting area by 20%, with expected proportional reductions in environmental impacts. Moreover, almost 20% of the area currently occupied by these roads could be returned to timber production.

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Authors' address – *Adresa autorâ*:

Prof. Ciro Hernández-Díaz, PhD.*
e-mail: jciroh@ujed.mx
Prof. Javier Corral-Rivas, PhD.
e-mail: jcorral@ujed.mx
Ramón Alvarado, MSc.
e-mail: alvonty@yahoo.com
Universidad Juárez del Estado de Durango
Institute of Silviculture and Wood Science
Fracc. Ciudad Universitaria, Blvd. Guadiana 501
Durango 34120
MÉXICO

Jesús Soto-Cervantes, mag. ing. silv.
e-mail: jesus9003@hotmail.com
Eusebio Montiel-Antuna, M.A.
e-mail: e.montiel@ujed.mx
Rodolfo Goche-Télles, PhD.
e-mail: jgoche@ujed.mx
Universidad Juárez del Estado de Durango
Faculty of Forest Sciences
Fracc. Ciudad Universitaria,
Blvd. Durangoy Río Papaloapan 34120
MÉXICO

* Corresponding author

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