# Analysis of the Relation Between Sewer System Failures And Urban Trees

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## ABSTRACT

Tree root growth and the problems associated with their interaction with urban infrastructure, such as roads and urban water pipes, are known. Understanding which tree species are more likely to cause intrusive events in sewer system, environmental, trees and pipe's characteristics that make more vulnerable the sewer system is a challenging goal because of the number of involved variables. Furthermore, sewer constructive quality, environmental and geological factors, trees and pipes sitting among others additional variables, make difficult to extrapolate results from other studies. This study develops analysis of an extensive structural and sediment-related failures data-base and a comprehensive tree inventory (containing 1'354.841 elements) of Bogotá (Colombia). To find a correlation among these two types of sewer system failures and the presence of trees capable of causing root intrusion, multiple regression models were developed. Three different models that relate spatially trees, pipes and failures were proposed. Three statistical models (Linear, Logit and Poisson) were implemented. Principal components analysis was developed to reduce the number of variables concerning tree measurements. Tree species more likely to cause root intrusion were identified. Models describing number of intrusive events are fitted for each species, showing that significance of variables may vary among species and buffer sizes. Some materials were identified as prone to present tree root intrusion and some environmental and pipe's characteristics were discarded.

## KEYWORDS
Root intrusion, Sewer system, Structural Failures, Sediment-related failures, Multiple regression models, Principal Component Analysis (PCA), Logit Model, Poisson Model.

## INTRODUCTION

Tree root growth interaction with urban infrastructure has been described and identified as
a worldwide problem in several previous studies (Day, 1991; Östberg et. al., 2012). Specially root interaction with urban sidewalks, curbs and gutters (Francis, 1996, Wong, 1998). Interactions among tree roots and pipes and other underground infrastructure are more challenging to study taking into account the difficulty to elaborate an accurate survey of intrusive events. Nevertheless, some cities and towns in which this analysis has been developed, have reported high percentages of root intruded pipes (e.g. Randrup, 2000; Stal,1998)

Efforts to quantify the magnitude and the costs associated to the conflict between tree root and urban infrastructures, have shown that cities spend substantial sums of money dealing with these problems (McPhersont & Peper, 1995; McPhersont & Pepert, 1996; McPherson, 2000; Randrup,2001). In addition to the financial costs, there are high costs in green infrastructure caused on trees (or their possible tree removal) (Randrup et.al., 2001).

A better understanding of the relation between sewer system failures and tree roots can be useful to develop proactive sewer system rehabilitation and maintenance strategies. Besides this, identifying the species that are more likely to cause root intrusion can also be helpful when building sewer system expansions by siting pipes at a considerable distance from existing mature trees or avoiding tree planting of such species in the sewer surroundings. This study aims to identify some of these problematic species and the variables that govern pipe failure events.

The next sections present the most important impacts of urban trees on sewer system and a brief literature review identifying variables related to root intrusion events. The case study used in this work presented, showing the benefits and limitations of the available databases (Bogotá, Colombia). Methodology presented, which involves Principal Component Analysis (PCA), three statistical models (Linear regression model, Logit and Poisson model), and three models that relate differently pipes, trees and failures. This study allowed to identify those species that are causing sediment-related and structural failures in Bogota city; as well as recognize other variables (such as pipe material) that have effect on failure events.

# IMPACTS OF URBAN TREES ON SEWER SYSTEMS

Sewer system are one of the urban infrastructures affected by tree roots. However, there is one important difference which makes stronger these negative effects in this infrastructure: tree roots seek for water and nutrients contained in sewer pipes, and once they access to this resource, they increase their capacity to penetrate pipes (Randrup et. al., 2001).

Sewer-tree roots interaction may cause structural and sediment-related failures, the first leads eventually to the structure collapse and the latter may cause flow problems. Both failures represent expensive costs to wastewater utilities and municipalities, which spend substantial amounts of money each year in root removal, pipe replacement and pipe renewal (Randrup et al., 2001). To have an accurate value of the costs generated by this interaction, damage to trees should also be considered; trees are an important and expensive component of the city ‘green infrastructure’ (McPhersont & Pepert, 1996).

In some cases, roots may not cause the initial crack, but they may expand existing openings, speeding up the structure’s weakening (Randrup et al., 2001). According to Randrup et al., 2001, root intrusion into pipes are reported to cause up to 50% of all sewer blockages , he found that roots are among the major contributors to sewer. Roots have a detrimental effect on sewer hydraulic conditions by generating a local flow restriction, which reduces flow velocity and favors the screening out of solids (Randrup et al.,2001).

Several studies have been carried out in order to understand the most relevant factors involved in the tree root intrusion process. Some analysis leads to the conclusion that there are specific species with several characteristics showing a higher intrusive potential. *Table 1* resumes the principal findings of several studies concerning tree and pipes parameters that influence positively the occurrence of sewer system failures.

*Table 1. Review of variables of pipes and trees involved in the root intrusion process*

| ***Variable/Parameter*** | ***Specification*** | ***References*** |
|---|---|---|
| *Diameter* | *150 mm* | *Pohls et. Al., 2002* |
| *Material* | *Vitreous* | *Pohls et. Al., 2002* |
| | *Clay* | *Wong et. al. 1988* |
| *Pipe's age* | *>30 years* | *Pohls et. Al., 2002* |
| *Pipe's depth* | ↓ | *Randrup et.al., 2001* |
| *Number of joints* | ↑ | *Ridgers et. al., 2006* |
| *Pipe-tree distance* | *< 7 m* | *Nicoll,1998* |
| | *<2-3m* | *Randrup et. al., 2001* |
| *Perimeter at trunk's high* | *11-20 cm* | *Wong et. al. 1988* |
| *Tree age* | *>15-20 years* | *Sydnor,2000* |
| | *40 years* | *Wagar and Baker,1983* |
| *Tree growing rate* | ↑ | *Barker (1983)* |
| *Circling barriers* | ↓ | *Costello, 1997* |

↑ Indicates a positive relation with the number of failures in the sewer system. ↓ indicates a negative relation.

Root intrusion in pipes is associated with a long list of variables, which includes those related to tree species, tree’s siting, pipe specifications and distances among trees and infrastructures. All those characteristics vary from site to site and it’s difficult to extrapolate results from studies carried out in different locations. Pipe construction quality for example (which may prevent from leaky joins and inadequate connections) (Stal and Rolf, 1998), is variable among the same municipal urban area. Tree species is also a regional variable and their growth is also characterized by environmental conditions, geology and urban soil characteristics (Pohls et al., 2002; Randrup et al., 2001).

## CASE STUDY

Regarding the relation among urban trees and sewer pipes no studies have been carried out in Bogotá in order to identify the most important variables involved in these events (according to the best knowledge of the author of this thesis). The environmental authority is aware of the conflict associated with trees and pipes. The city wastewater utility has evidence of the costs incurred in maintenance and repairing actions. However, species more likely to generate intrusive events have not been statistically identified and correlation among specific tree and pipe variables has not yet been quantified.

Available information has been gathered in order to develop multiple analysis with the purpose of identifying the most relevant variables in the tree root's intrusive events in sewer system. Governmental entities in charge of urban tree planting counts on a long inventory of tree's in the Bogotá's urban area (307 km2) which contains up to 1.2 million of tree elements. The wastewater utility has compiled an exceptionally long and spatially detailed data set based on customer complaints, covering the 7.5 million inhabitants of Bogotá. The 7,678 km of sewer pipe in the city are represented in a georeferenced database which brings together their more relevant characteristics; such as material, pipe diameter, age, length, pipe slope and depth among others.

**Urban tree inventories**

Bogota's tree inventory contains about 1.3 million elements and includes, along with the location of each element tree or burst in the urban area of the city, specification of species and subspecies, the total high, physiology, equatorial diameter, basal perimeter, trunk's high and perimeter, degree of angle, and a brief description of the leaves and the site location. *Figure 1* shows some of the variables under study, which are consigned in the urban tree inventory. This information was obtained from Bogota's urban tree planting authority, which elaborate an accurate tree census on 2007.

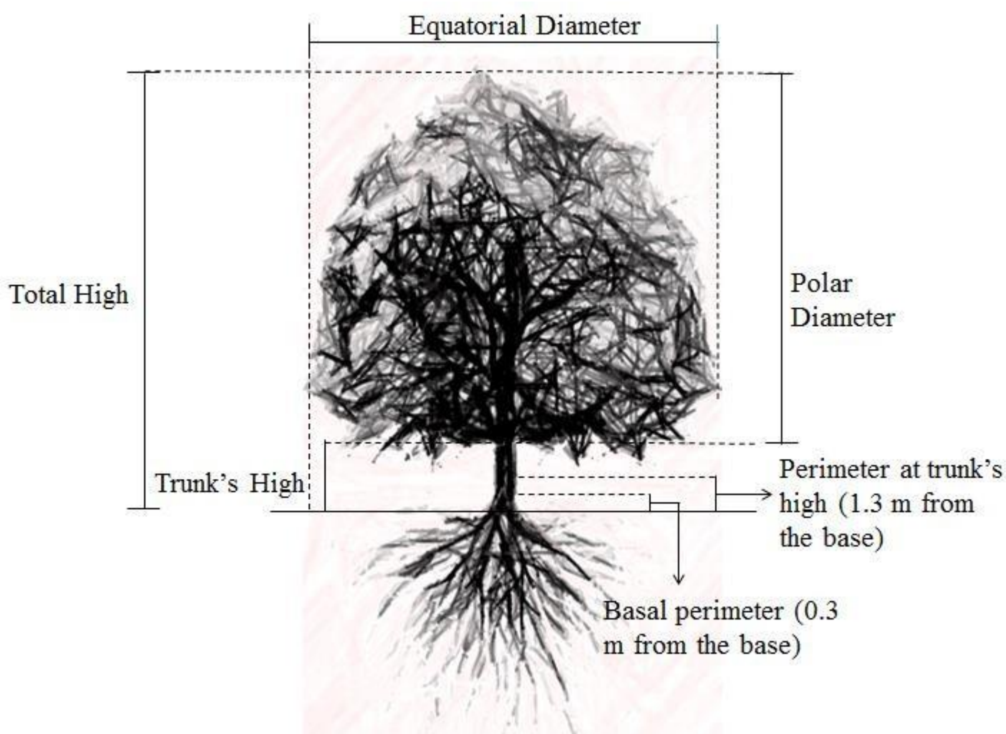


*Figure 1. Tree variables under study. Modified from http://www.dingtwist.com/amazing-trees/*

From the 324 of tree species identified in the urban area of Bogotá, urban tree planting authority have pointed out 50 tree species capable of causing root intrusion, based on observations on visible infrastructure (sidewalks and ways). Among these species are found *Pinus spp., Croton spp., Ficus spp., Acacia spp., Myrsine guianensis, Magnolia grandiflora, and Querus humboldtii,* which all share a fast-growing characteristic. *Annex 1* lists these 50 species, color is codified for the root's capacity to generate intrusion events, classified by the JBB. Yellow is for low capacity, orange for medium and red for high.

To analyze only the species on the sewer system surroundings, a 10 meters buffer parallel to the sewer pipes was made, which allowed us to filter the 145,108 trees capable of causing root intrusion lying within the buffer. It is assumed that tree species that have shown problems with roads are expected to be highly intrusive in sewer pipes. From the 1'354.841 species presented in Bogota's urban area, 38% are located in the 10 meter buffer parallel to the sewer system, and from this percentage, about 24% of specimens correspond to tree species classified as capable of causing root intrusion. Urban tree planting authority also report recommended species to be planted nearby urban service networks. In contrast to the percentages previously reported, recommended species within the 10 m buffer is around 16%.

## Failure databases

Bogotá waste water utility has found multiple events of root intrusion on CCTV inspection, which pointed out failure events caused by *Fraxinus chinensis* and *Liquidambar styraciflua*. Unfortunately there is not a sufficiently wide data-base record to identify statistically the characteristics of the places and pipes most likely to present root intrusion.

However, waste water utility has a wide data set of sediment-related and structural failures, which synthetize 9 years of failure records (June 2004-June 1013) (see Rodriguez et al.(2012) for further details about the sediment-related failures database). These long and spatially detailed data bases compile a large amount of information to be gathered and analyzed. However it must be taken into account that there is not available information concerning the effective intrusive root events. Causes for the sediment-related and structural failures reported may be diverse and only a portion of this information is effectively attributed or influenced by tree root intrusion in the sewer system.

The information available for this study is a long period (2004-2013) compilation of sewer system failure events which, when gathered with pipe's and tree's characteristics, allows robust statistical analysis. However, has strong limitations associated to the ignorance of the real cause of the failure. On the other hand, the analysis are subject to georreferencing mistakes, which become more important when the models proposed are smaller in scale.

## METHODOLOGY

Taking into account that tree urban census was conducted on 2007, both sewer failure databases were filtered in order to find the relation among tree variables and failures reported in that same period. In 2007, 4,936 and 19,498 structural and sediment-based related failures were reported respectively. To find a correlation between the two types of sewer system failures with the presence of trees capable of causing root intrusion, the city was subdivided in 9,658 grid squares of 0.03 $km^2$ each, covering an approximately total pipe length of 7,678 km. Each of the 145,108 trees were associated with a grid cell, keeping all the tree characteristics information. *Figure 2* shows the number of trees per grid, which evidence the presence of a higher density of urban trees in the north part of the city.

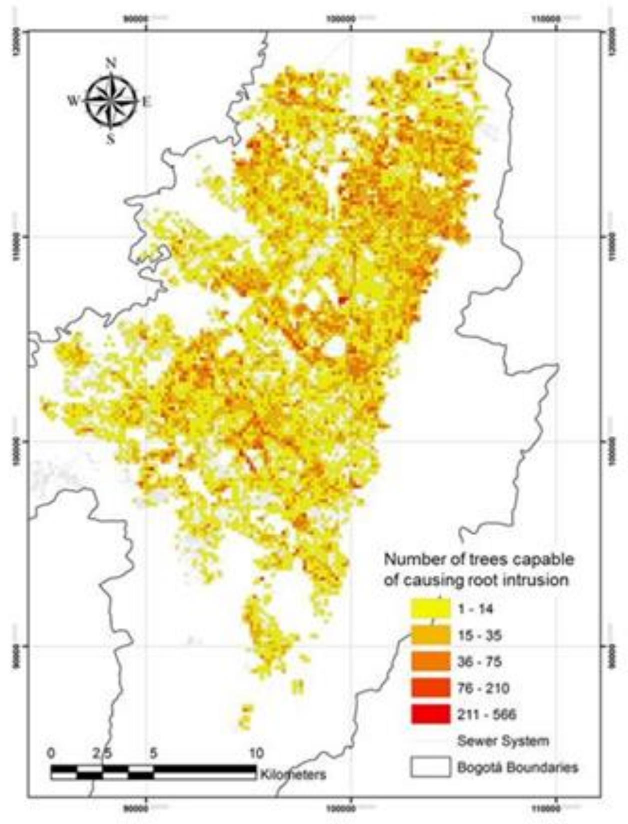


*Figure 2. Bogota density map of trees capable of causing root intrusion events in 0.03 $km^2$ cells*

Failures and pipes were also overlapped with the grid, resulting in a data base of grid cells with the following attributes: average pipe diameter, average depth and age, and total length. Following this procedure the final result is a database with 145,108 observations (one per potential possible intrusive tree), each associated to an average pipe depth, total length and number of registered failure records (both sediment-related and structural).

After obtaining first results, and because of the uncertainty related to associate all cell-grid failures with a single tree (0.03 $km^2$ area for a single tree to influence), further models were proposed, including additional variables listed in *Table 2*. Environmental variables were obtained as raster layers that allowed the extraction of the exact value using x and y coordinates of the tree.

*Table 2. Tree, pipe and environmental selected variables to be included in the regression models*

| ***Tree Variables*** | ***Sewer System Variables*** | ***Environmental*** |
|---|---|---|
| *Total high** | *Pipe depth** | *2006 Precipitation** |
| *Trunk high** | *Pipe material*** | *Water table depth** |
| *Perimeter at trunk's high** | *Pipe diameter*** | |
| *Basal perimeter** | *Pipe length** | |

| | | |
|---|---|---|
| *Equatorial diameter** <br><br> *Polar diameter** <br> *Tree sitting**** <br> *Tree physiology*** <br> *Root Exposition**** | *Pipe age** <br> *Minimum distance from the tree** | |

**Numerical variables*
***Categorical variables*
****Dummy variables (that represent absence/presence)*

In order to present the proposed models, the following symbology was determined:

$i = Cell\ row$ $\{i = 1,2,3,4 \ldots..257\}$
$j = Cell\ column$ $\{j = 1,2,3,4 \ldots..173\}$
$c = Cell\ sector\ (defined\ by\ a\ row\ i\ and\ a\ column\ j)$ $\{k = 1,2,3,4 \ldots..44461\}$
$S = Total\ number\ of\ cells = i \times j = 44461$

*Tree's variables*

$l = Tree\ specie$ $\{l = 1,2,3,4 \ldots..50\}$
$h = Tree\ specimen$ $\{h = 1,2,3,4 \ldots..\mathbf{145,108}\}$
$N_l = Number\ of\ tree\ of\ l\ specie$
$N_{lc} = Number\ of\ tree\ of\ l\ specie\ in\ sector\ c$
$X = A\ tree\ numerical\ variable\ (see\ Table\ 2)$
$\overline{X}_l = Mean\ X\ parameter\ for\ specie\ l$

$$\overline{X}_l = \frac{\sum_{i=1}^{N_l} X_l}{N_l}$$

$\overline{X_{lc}} = Mean\ X\ parameter\ for\ specie\ l\ in\ sector\ c$

$$\overline{X_{lc}} = \frac{\sum_{i=1}^{N_l} X_{lc}}{N_{lc}}$$

**Dummy and categorical tree variables were not included in models in which averaging was required.*

*Pipe's variables*

$N_c = Number\ of\ pipes\ in\ sector\ c$
$L_{ck} = Length\ of\ pipe\ k\ that\ belongs\ to\ sector\ c$
$LT_c = Total\ pipe\ length\ in\ sector\ c$
$Y_c = A\ pipe's\ categorical\ variable\ (see\ Table\ 2)$
$\widehat{Y_c} = Mode\ of\ Y\ variable\ among\ pipes\ belonging\ to\ sector\ c$

$$\widehat{Y_c} = mode(Y_c)$$

$J_c = a\ pipe's\ numerical\ variable\ (see\ Table\ 2)$
$\overline{J_c} = Mean\ of\ J\ variable\ among\ pipes\ belonging\ to\ sector\ c$

$$\overline{J_c} = \frac{\sum_{i=1}^{N_c} J_{ck} * L_{ck}}{\sum_{i=1}^{N_c} L_{ck}}$$

*Observed Failures*

$$q = failure\ type \qquad \begin{cases} sediment - related\ failures \\ structural\ failures \end{cases}$$

$F_{hq} = Number\ of\ q\ type\ failures\ in\ tree\ h\ surroundings$
$F_{cq} = Number\ of\ q\ type\ failures\ in\ in\ sector\ c$
$F_{lq} =\ Number\ of\ expected\ q\ type\ failures\ caused\ by\ specie\ l\ (model\ outcome)$

**MODELS**

**Model 1: 'Failures and trees per specie in grid'** (Evaluates the influence of specie $l$ in the failures of grid cell $c$)

*Figure 3* illustrates this model, in which a grid cell (170 x 170 m) was used to spatially relate trees, pipes and failures. In each grid cell, failures that fall within were counted, and the pipe characteristics were averaged in order to obtain mean sewer system characteristics per grid cell. The number of observations is the total number of tree species per grid cell, each associated with the sector pipe's characteristics. This means that if more than one tree of the same specie lays in the same grid cell c, the characteristics are averaged to obtain a single observation per tree species in grid cell c.

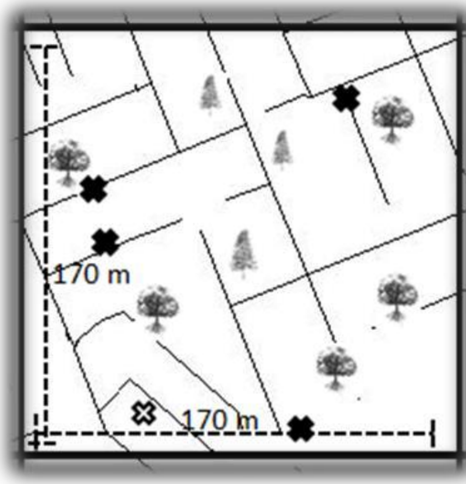

*Figure 3. Model 1 ilustration: failures and trees (per specie) in grid cell*

**Model 2: Failures and pipes in tree's surrounding.** This model considered the failures that lay within a circular buffer around each tree, see *Figure 4*. The size of the buffer variable and is determined by the equatorial diameter of each tree. This variable was used as proxy to the root's extend. The pipe characteristics were averaged using all the pipes that lay inside the equatorial diameter buffer. In this way, each tree is associated to its own number of failures and its own pipe surroundings characteristics.

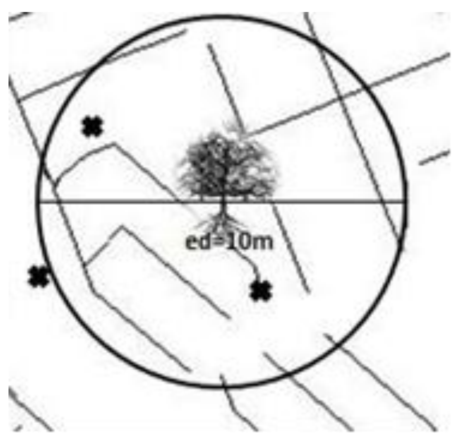

*Figure 4. Model 2 ilustration: failures and pipes in tree's surroundings.*

**Model 3: Failures associated to closest pipe. Pipe associated to closest tree.**

In this last model (see *Figure 5)*, each tree is paired with a single pipe (the closest in a linear distance), which at the same time have been associated with the failures. One failure can only be paired with one pipe, but one pipe can present more than one failure if it happens that two failures are closer to it in contrast with the rest of pipes.

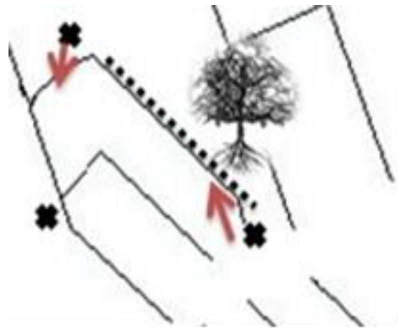

*Figure 5. Model 3 ilustration: Failures associated to closest pipe. Pipe associated to closest tree*

## STATISTICAL ANALYSIS

### Multiple Linear Regression Model

The term "Multiple" makes reference to multiple regressor variables, or explicative variables (Montgomery et.al., 2001). The model is named 'linear regression' because of the nature of the relationship among the regressor and the answer variable, it is defined as follows

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon$$
$$E(y|x) = y$$

Where $\varepsilon$ is the error and corresponds to the deviation of the conditional mean to the observation. The coefficients $\vec{\beta}$ are calculated by the Method of Least Squares or by the Method of Maximum Likelihood. The significance of each estimator is tested with the use of t statistic.

Where $H_0: \beta_k = 0$, $H_1: \beta_k \neq 0$ and

$$t = \frac{\widehat{\beta_k}}{\sqrt{\frac{MS_{Res}}{S_{xx}}}}$$

$MS_{Res}$ is the residual mean square significance of each estimator is tested with the use of t statistic and

$$S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2$$

Where $n$ is the number of observations.

### Logistic Regression Model

In contrast to the Linear Regression Model, the logistic regression' outcome is a binary or dichotomous variable. Also, the outcome $\hat{y}$ do not correspond to the estimator of the observation $y$; in the logistic regression, the outcome $\pi(x)$ take values among 0 and 1, which corresponds to the probability to obtain a "success" (which for this work is 'failure').

$$\pi(x) = E(Y|x)$$
$$0 \leq E(Y|x) \leq 1$$

The form of the logistic regression is:

$$\pi(x) = \frac{e^{\beta_o + \beta_1 x}}{1 + e^{\beta_o + \beta_1 x}}$$

And the outcome variable given $x$ is:

$$y = \pi(x) + \varepsilon$$

The Logit Transformation is used to obtain the desired properties of the regression model, converting the relation among the function $\mathbf{g(x)}$ and the parameters linear:

$$g(x) = \ln\left[\frac{\pi(x)}{1 - \pi(x)}\right] = \beta_o + \beta_1 x$$

In contrast to the linear regression, the estimators $\hat{\beta}$ cannot be directly interpreted. The $\hat{\beta}$s quantify the change in the odds logarithm when $x_i$ increases a unity.

$$ODDS\colon \frac{Probability\ \ of\ a\ "success"}{Probability\ \ of\ not\ a\ "success"}$$

$$ODDS = \frac{\pi(x)}{1 - \pi(x)}$$

Statistical packages such STATA, reports not only the estimators $\hat{\beta}$ but also the odds ratio, which allow the comparison among the "success" odds when changing in one unit the value of a single variable under the same conditions (which means not changing the other variables).

$$ODDS\ RATIO = \frac{ODDS\left(x_j + 1\right)}{ODDS\left(x_j\right)}$$

**Principal Components Analysis (PCA)**

This technique is used to reduce the large dimension of a data set consisting on interrelated variables. This goal must be achieved by retaining as much as possible the variation present in the original data set (Jolliffe, I.T.,2002).

Consider a $x$ vector of $p$ variables. PCA look for few ($\ll p$) derived variables based on variance analysis. This is achieved by looking for $i$ linear functions $\propto_i'\ x$ of the elements of $x$ having maximum variance. $\propto_i'$ is the $i_{th}$ component of $p$ constants; the first component is defined as follows:

$$\propto_i'\ x = \alpha_1 x_1 + \alpha_2 x_2 + \cdots + \alpha_p x_p = \sum_{j=1}^{p} \alpha_j x_j$$

From the original model $\vec{y} = \vec{x}\vec{b} + \varepsilon$ (where $\vec{y}$ is the independent variable, $\vec{x}$ are the observations, $\vec{b}$ are the estimators or coefficients and $\varepsilon$ are the errors), and using the eigenvectors of the $\vec{x}$ the transformed variable $W$ are obtained:

$$\vec{w} = \vec{x}C$$

Where $C$ correspond to the eigenvectors. Taking into account that the eigenvectors are orthogonal, then $\vec{w}$ is also orthogonal.

The "new model" can be written as follows:

$$\vec{y} = \vec{w}\vec{d} + \varepsilon$$

The estimators of the "new model" $\vec{d}$ can not be interpreted directly. It is necessary to express those coefficients in terms of the original coefficients $\vec{b}$. This can be calculated as follows:

$$\vec{b} = \left(\overrightarrow{x^T}\vec{x}\right)^{-1}\overrightarrow{x^T}\vec{y}$$
$$\vec{b} = \left(\overrightarrow{x^T}\vec{x}\right)^{-1}\overrightarrow{x^T}(\vec{w}\vec{d} + e)$$
$$\vec{b} = \left(\overrightarrow{x^T}\vec{x}\right)^{-1}\overrightarrow{x^T}(\vec{x}C\vec{d} + e)$$
$$\vec{b} = C\vec{d}$$

Once coefficients $d$ are calculated, they can be interpreted in terms of $b$ by using this equation.

Although the interpretation of the PCA is simple, experts recommend to gather variables whose set have some intuitive meaning. This can only be achieved when original variables are well understood.

**Poisson Regression Model**

This model is count data regression model, whose data is the outcome of an underlying count process in time (Winkelmann R., 2008). This model describes the number of occurrences of an event for a given time T. To use this model is necessary to fulfill the assumptions of independence and constant probabilities for the events. The Poisson distribution can be defined as follows (Winkelmann R., 2008):

A random variable R with discrete distribution $\in \mathbb{Z}^+ \cup 0 = 0,1,2, \dots X$ follows Poisson distribution if the probability function is as follow:

$$P(X = k) = \frac{e^{-\lambda}\lambda^k}{k!}, \lambda \in \mathbb{Z}^+, k = 0,1,2, \dots$$

The expected value and variance of the Poisson distribution is defined as:

$$E(X) = \lambda$$
$$Var(X) = \lambda$$

The Poisson Regression Model (PRM) considers the non-negativity integer nature of the dependent variable. This distribution has one only positive parameter $\lambda$ which corresponds to the mean and variance.

For convenience, $\boldsymbol{\lambda}$ is specified as an exponential function of a linear combination of the explanatory variables $\vec{\mathbf{x}}$

$$\lambda = \exp(\beta_1 + \beta_2 x_2 + \cdots + \beta_k x_k)$$

Positive coefficients $\beta_j$ indicate as well as in linear regression, positive values. However, as well as the Logit Model, there is a quantity of interest named the *incidence rate ratio (IRR),* which is obtained by simply exponentiating the coefficient estimate $\overrightarrow{\beta_k}$. The IRR describes the relative change in the incidence rate for one unit change in $x_j$ (Winkelmann R., 2008).

# RESULTS

Preliminary analysis aimed at relate observed failures with the number of intrusive trees in each cell-grid *Figure 6 (a)* and *(b)* shows the counterintuitive result obtained with sediment- related failures and structural failures respectively. These unexpected results were attributed firstly to the need of differentiating among tree species (because some tree species may not be as intrusive as others). On the other hand, evidence points that a higher distance among infrastructure tend to diminish the probability of having an intrusive event.

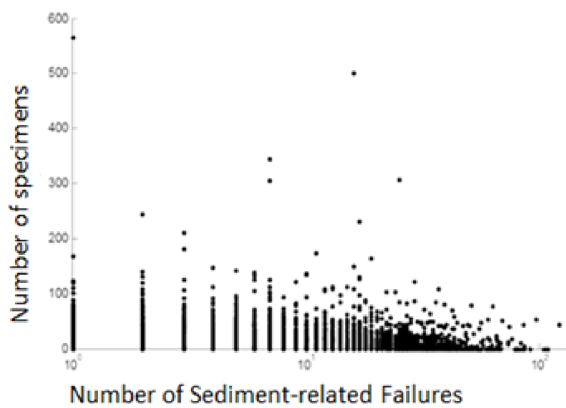


*Figure 6(a). Number of sediment-related failures vs. No. of trees capable of causing root intrusion*

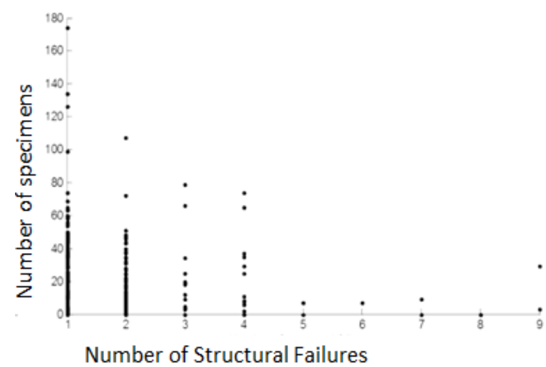


*Figure 6(b). Number of structural failures vs. No. of trees capable of causing root intrusion*

To understand the effect of the grid and buffer size, analysis were developed for each tree species, for three different grid sizes and with two new buffer sizes (5 and 1 meter buffers). A decreasing trend in the number of failures (structural and sediment-related) was observed in all species when increasing the number of trees. *Figure 7* shows results obtained for the structural failures with one particular specie Pinus. Once more, unexpected results were obtained

For further analysis the noise introduced by specimens that may not be capable of causing root intrusion were left out of the analysis. This time, the counterintuitive results were attributed to: (i) there may be trees that are not mature enough or (ii) are not sufficiently close to the sewer system; (iii) there exist high sensitivity to the grid's size used for the analysis. These noises were intended to be corrected as follows.

In order to eliminate the effect of the grid's size in the number of failures observations, sediment-related and structural failures were normalized using the total length of the pipe among the grid. In this way, linear regression models were used with the number of observed structural failures/km of pipe and number of observed sediment-related failures/ km of pipe as the response variable. As accurate tree root depths are not available, different proxy variables such as tree's high and tree's breast perimeter (PAP) were used. PAP) were used.

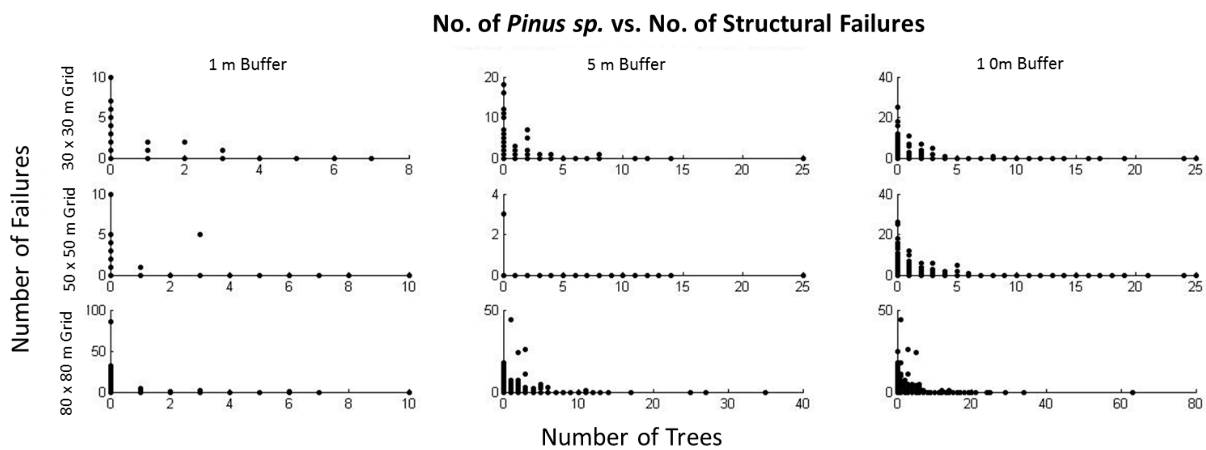


*Figure 7. Number of Pinus vs. observed structural failures*

Because of the great amount of pipe's and tree's variables which have reported theoretical correlation with structural and sediment related failures (see Table 1), selection of the most relevant, or at least more intuitive, variables were selected. In this order of ideas, multiple linear regressions for each species under study (50 different species) and for each distance buffer (3 sizes) were generated for the two types of failures. Answer variable is the number of failures normalized with the pipe length among each grid and independent variables used are tree's high, PAP and pipe's depth.

Some species previously considered as highly intrusive, based on observations with sidewalks and ways, (Investigation and Scientific Development Center Jardín Botánico de Bogotá José Celestino Mutis (JBB)) had a limited number of failure observations (none or only one). *Table 3* summarises intrusive species that did not show a significant relation to pipe failures.

*Table 3. Species that did not show a significant relation to pipe failures due to limited number of failure observations*

| Sediment-related failures | Structural failures |
|---|---|
| ***Eucalyptus spp.*** | ***Eucalyptus spp.*** |
| *Eucalipto común* | *Eucalipto común* |
| *Eucalipto plateado* | *Eucalipto plateado* |
| *Eucalipto manchado* | *Eucalyptus camaldulensis* |
| ***Cupressus spp.*** | ***Pinus spp.*** |

| | |
|---|---|
| *Ciprés japonés* | *Pino azul* |
| ***Pinus spp.*** | *Pino pinaster* |
| *Pino azul* | *Pino Australiano* |
| *Pino montezuma* | |
| *Pino libro* | |

Most of the identified species were specific for only one type of failure (sediment-related or structural), except for the species *Eucalyptus globulus*, *Eucalypto pulvurulenta* and *Psolarea pinnata.* Also, the conclusions drawn by the regression models of each buffer size were different among the same species.

The linear models were developed to fit three variables: pipe depth, three height and perimeter at trunk's height. For 50% of the regressions and for 63% of the tree species, the variable pipe depth was found to be significant, which means that should be present in the linear model. Tree's height was significant in 16% of the regressions and 29% of tree species, while perimeter at trunk's height was only taken into account for the 26% of the tree species and in 10% of the regressions.

Correlation coefficients showed that for both structural and sediment-related failures, about 69% of the species showed negative relation among pipe depth and observed structural failures. Only 35% and 36% of the information showed expected positive correlation among perimeter at trunk's height and tree height with the independent variable. On the other hand, obtained results showed that there is a great sensitivity to buffer size changes. For sediment-related failures and structural failures, 26 and 21 tree species' regressions respectively showed a trend when buffer size is gradually reduced (from 10 to 5 and then to 1 meter). In the majority of the tree species' regressions, the trend was to decrease its number of explicative variables when reducing buffer size.

Regression parameters (using a 0.08 significance level) for sediment-related and structural failures and for the three most frequent species are presented in *Tables 4* and *5*, respectively. Missing values represent that such variables were not significant in the linear regression model and do not describe the response variable. *Tables 4* and *5* show that in these cases and for a significance level of 0.08, pipe depth reported a negative relation with the failures, which supports the theory that deeper pipes are less prone to experience tree root intrusion problems. The three species reported in *Tables 4* and *5* show that for different buffer distances, regression models are different. For example, *Tabebuia ochracea* model for the 1 m buffer illustrates a regression whose three variables showed to be significant, while the model for the 5 m buffer shows only pipe depth as a significant variable; finally, for the 10 m buffer, the model involved pipe depth and PAP variables as explicative variables. Significance of variables in all regression models were evaluated at a 0.08 significance level.

*Table 4. Regression model parameters for the three most frequent intrusive species (structural failures)*

| Species | Buffer distance | Intercept | Tree height | PAP | Pipe depth |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| *Ficus benjamina* | 10 | -0.059 | - | - | -0.001 |
| | 5 | 0.909 | - | - | -0.446 |
| | 1 | - | - | -0.193 | - |
| *Tabeluia ochracea* | 10 | 1.188 | 0.020 | - | -0.567 |
| | 5 | 1.522 | 0.014 | - | -0.725 |
| | 1 | 1.232 | -0.044 | 0.286 | -0.528 |
| *Cupressus lusitanica* | 10 | 0.734 | - | 0.031 | -0.332 |
| | 5 | - | - | - | - |
| | 1 | - | - | - | - |

*Table 5. Regression model parameters for the three most frequent intrusive species (sediment-related failures)*

| Species | Buffer distance | Intercept | Tree height | PAP | Pipe depth |
|---|---|---|---|---|---|
| *Ficus benjamina* | 10 | 6.343 | - | - | -2.956 |
| | 5 | 7.223 | - | -0.209 | -3.380 |
| | 1 | 4.682 | - | - | -1.842 |
| *Tabeluia ochracea* | 10 | 3.437 | - | 0.171 | -1.418 |
| | 5 | 6.268 | - | - | -2.826 |
| | 1 | 4.261 | -0.0465 | 0.253 | -1.865 |
| *Cupressus lusitanica* | 10 | 4.568 | - | - | -1.918 |
| | 5 | 2.124 | - | - | -0.775 |
| | 1 | 14.006 | - | - | -6.523 |

Regression models showed to be highly sensible to buffer size changes: this means that the linear distance between trees and sewer pipes may lead to different results. In both types of failures (structural and sediment-related), the majority of the regressions gradually decrease the number of significant variables when reducing buffer size. Nevertheless, there was a considerable proportion of the tree's regressions that did not evidence any trend (16 tree species for sediment-related failures and 21 for structural failures, both from the total 50 tree species under study). In order to clarify these findings, additional fits using the minimum linear distance between each tree and the closer sewer pipes were proposed.
Until this point only linear regression models were used in order to describe the observed failures. For implementing the tree models exposed, further considerations must be analyzed.

When filtering the available records spatially using the equatorial diameter of each tree, the number of observed failures decreased. Up to this point, the failures in the grid cell associated to each tree (mean of 18 for sediment related failures and 5 for structural failures) became significantly less (mean of 3 for sediment related and 1 for structural failures). This important change of the order of the response variable made the assumptions for the linear regression model difficult to fulfill and for this reason, also Logit and Poisson models were used. For this last analysis three statistical models were used (Linear, Logit and Poisson), the same two types of failures (structural and sediment related), the 50 tree species identified as prone to cause root intrusion, and three data bases gathered according to the models (with different spatial relations) exposed before. In this order of ideas, a total of 900 regressions were runned.

These analysis involved a much bigger number of variables, which included some tree's variables, pipe's variables and other grouped under the name 'environmental' variables (See Table 2). Because of the large number of variables and taking into account that first six tree variables listed in *Table 5* are measurements of the tree size, a principal component analysis was developed to replace this six measurements with a few composed variables. Because the first findings pointed that it was necessary to differentiate each specie, PCA analysis was developed for each of the 50 species under study. *Figure 8* (a) and *8 (b)* shows each variable's weight in principal component 1 and 2, respectively. Each bar in the graph represents one tree specie.

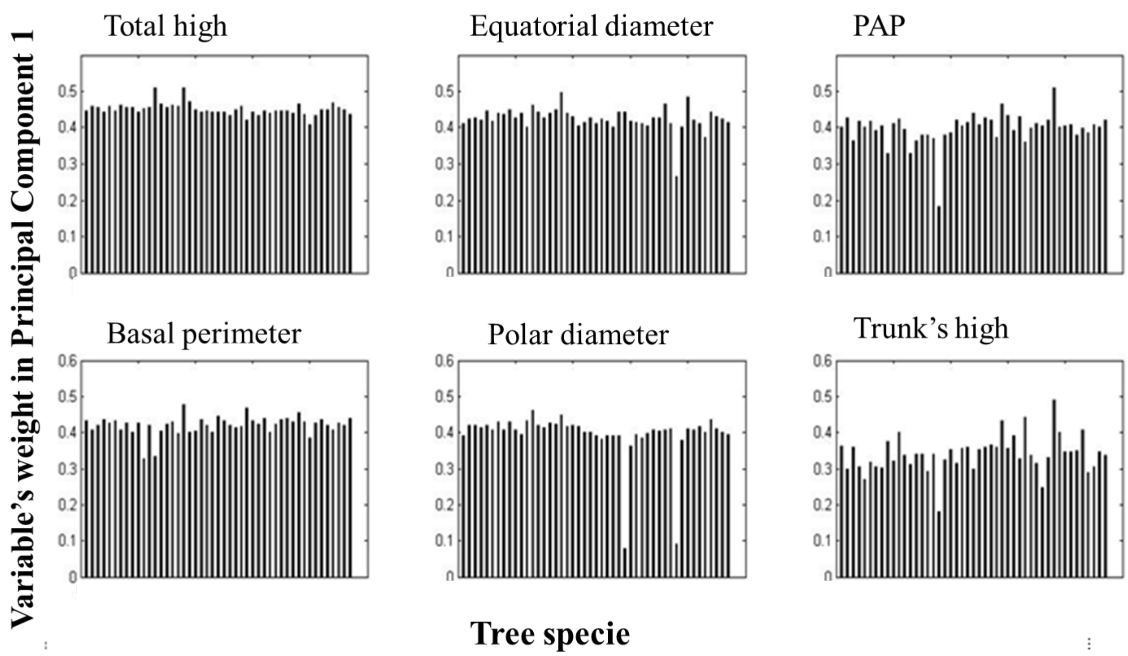


*Figure 8(a). Weight of each tree variable in principal component 1*

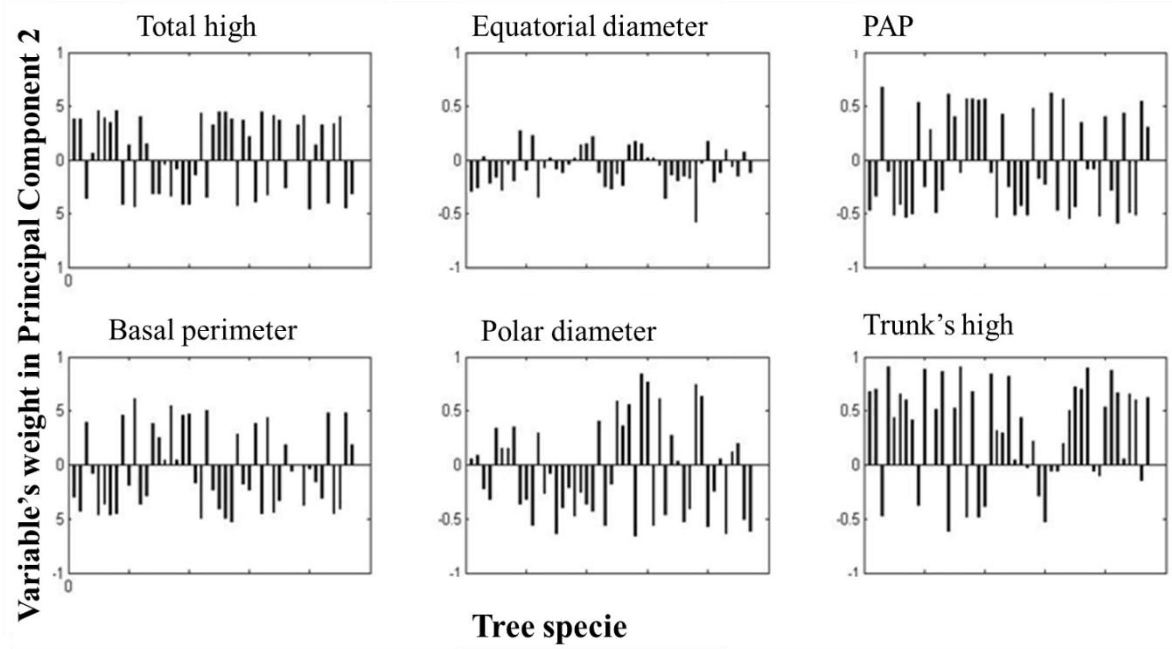


*Figure 8(b). Weight of each tree variable in principal component 2*

The analysis showed that in the majority of the cases more than the 90% of the variability of the original variables could be described with the first two or three principal components, which we called *measurement of the tree.* Also, the weights of each tree variable in the first component was around 0.4 for each original variable, which means that all the variables are contributing in the same proportion to the component *measurement of the tree*. For the second component, there is more variability among species, which highlight the need to develop individual analysis per tree species. In this case, some variables (such as equatorial diameter) present lower weights in contrast with principal component 1.

Results showed that about 30% of the sediment-related failures regressions had the variable *measurement of the tree* as significant and around the 12% for the structural failures (in both cases using a significance of 0.1). *Table 6* resumes those species that consistently (in all models) showed evidence to affirm that failures in the tree surroundings may be correlated with tree characteristics.

*Table 6. Species that consistently showed statistical evidence to be prone to cause root intrusion*

| **Sediment-related failures** | **Structural failures** |
|---|---|
| *Guayacán de manizales* | *Guayacán de manizales* |
| *Urapán* | *Chicalá flor amarillo* |
| *Caucho benjamín* | *Ciprés pino* |
| *Caucho de la india* | *Eucalipto pomarroso* |
| *Ciprés italiano* | *Sauce llorón* |
| *Eucalipto cinirea* | |

| | |
|---|---|
| *Pino candelabro*<br>*Pino pátula*<br>*Sangregado bogotensis* | |

The answer variable of the logit model is 1 for presence of failures and 0 for absence. When implementing the model, the statistical package is capable of identifying those tree codes whose response variable is consistently 0. This means that any tree of the corresponding species have presence of failures in its surroundings. *Table 7* evidences that there are more tree species listed in structural failures, an expected result taking into account that the structural failures are almost 4 times less failures than sediment-related failures. *Table 7* shows the list of those species that were consistently pointed out as not prone to cause failures by the three models.

*Table 7. Species that consistently showed statistical evidence that they are not related to sewer system's failures*

| **Sediment-related failures** | **Structural failures** |
|---|---|
| *Acacia blanca* | *Cucharo* |
| *Caucho lira* | *Acacia blanca* |
| *Eucalipto manchado* | *Caucho tequendama* |
| *Pino hayuelo* | *Caucho lira* |
| *Pino azul* | *Ciprés italiano* |
| *Sangregado magdalensis* | *Ciprés Japonés* |
| *Pino pinaster* | *Eucalipto plateado* |
| | *Pino hayuelo* |
| | *Pino azul* |
| | *Pino australiano* |
| | *Pino pinaster* |

As well as the preliminary analysis developed, the models showed some differences in results, for example, in some cases the model showed failures increases with depth and other showed that they decreased instead. Tables from 8 to 10 show the results obtained for Model 3 in the case of sediment-related failures (Model 3: Failures associated to closest pipe. Pipe associated to closest tree.).

*Table 8. Linear regression model results for sediment-related failures sig=0.08)*

| **Variable** | **Value** | **$\beta$** | **p-value** |
|---|---|---|---|
| Tree Location | Confined | 0.029 | 0.00 |
| **Physiology** | | | |
| | Semi-Deciduous | 0.021 | 0.00 |
| | Perennial | 0.029 | 0.00 |
| **Material** | | | |
| | Reinforced Concrete | -0.056 | 0.00 |
| | Concrete Reinforced | -0.09 | 0.00 |
| | PVC | 0.034 | 0.08 |

| | | | |
|---|---|---|---|
| | Stoneware | 0.31 | 0.00 |
| | Polyester Fiberglass reinforced | -0.087 | 0.00 |
| | Brick | 0.03 | 0.05 |
| Precipitation (2006) | | 0.0000135 | 0.04 |
| Pipe Diameter | | -0.00024 | 0.04 |
| Pipe Length | | 0.00045 | 0.00 |
| Pipe Age | | (-)7.58xe-7 | 0.00 |

*Table 9. Logit Model. ODDS results for sediment-related failures (sig=0.05)*

| Variable | Value | OR | p-value |
|---|---|---|---|
| Tree Location | Confined | 1.188 | 0.00 |
| **Physiology** | | | |
| | Semi-deciduous | 1.351 | 0.00 |
| | Perennial | 1.195 | 0.00 |
| **Material** | | | |
| | Reinforced concrete | 0.456 | 0.00 |
| | PVC | 0.615 | 0.00 |
| | PVC (Opened Profile) | 0.473 | 0.02 |
| | Stoneware | 0.31 | 0.00 |
| | Polyester fiberglass reinforced | 0.19 | 0.00 |
| | Brick | 1.168 | 0.01 |
| Precipitation (2006) | | 1.001 | 0.00 |
| Pipe Diameter | | 0.988 | 0.00 |
| Pipe Length | | 1.006 | 0.00 |
| Pipe Age | | 0.999 | 0.00 |

*Table 10. Poisson Model. IRR results for sediment-related failures (sig=0.05)*

| Variable | Value | IRR | p-value |
|---|---|---|---|
| **Physiology** | | | |
| | Semi-deciduous | 1.34 | 0.00 |
| | Perennial | 1.22 | 0.00 |
| **Exhibit Roots** | | | |
| | No | 0.946 | 0.00 |
| **Material** | | | |
| | Reinforced concrete | 0.53 | 0.00 |
| | PVC | 1.07 | 0.02 |
| | PVC (Opened Profile) | 0.85 | 0.05 |
| | Stoneware | 1.34 | 0.00 |
| | Polyester fiberglass | 0.19 | 0.00 |

| | | | |
|---|---|---|---|
| | reinforced | | |
| | Brick | 1.28 | 0.00 |
| Precipitation (2006) | | 1.001 | 0.00 |
| Pipe Diameter | | 0.991 | 0.00 |
| Pipe Length | | 1.004 | 0.00 |
| Pipe Age | | 0.999 | 0.01 |

From these results it is important to mention the coherence found among the three statistical models applied to Model 3. Environmental and pipe's characteristics (except for material) do not showed an important effect on the number of failures observed. The majority of the pipe materials have a lower odds to present failures in contrast to the concrete (specially reinforced concrete, polyester fiberglass reinforced and PVC-Closed Profile. The materials that are more prone to fail are brick and stoneware. Poisson model for this case showed significant the variable *Exhibit Roots*, however, the IRR obtained was close to 1, showing that this variable has not an important effect in the failure observed.

Regarding all the models, only consistent results will be provided next. This means that for the three models proposed to relate failures, pipes and trees, as well as the three statistical models used, same conclusions were obtain for each particular variable.

To be highlighted from these results there are some important facts: According to logit model, tree sited in confined spaces (with protection) have a higher odds to generate sediment-related failures than those planted without protection. This may be explained by the reason that protection is designed to avoid lateral growth of the roots, making their growth leaded to higher depths. Pipe diameter, pipe length and pipe age didn't show an important effect on the number of failures observed neither for structural failures nor for sediment-related.

Poisson and Logit models showed that any of the environmental variables, nor water table depth nor precipitation explain the observed failures. This was showed in near-to-cero coefficients in linear regressions, and OR and IRR near to one.

Semideciduous and perennial trees showed a higher odds in comparison to deciduous tree. The coefficient obtained in the models showed that these types of threes tend to have around 1.2 higher odds to present failures. On the other hand, the models presented contrasting conclusions about the differences among tree that exposes roots or not. Moreover, in the majority of the cases, this variable wasn't even significant, letting us to the conclusion that the presence or absence of root over ground has no relation with the failures underground.

*Table 11 and 12* resumes the most consistent results obtained by the models. Table 11 specifies variables that influence the probability of failure and Table 12 those that did not show evidence to affect the incidence of failures. Both tables contain results that contradict some of the literature review, this is going to be discussed in the conclusion section.

*Table 11. Odds ratio of variables that showed evidence to influence pipe's failure probability*

| ***Variable/Parameter*** | ***Description*** | ***Sediment-related failures*** | ***Structural failures*** |
|---|---|---|---|
| *Pipe's material* | *Stoneware* | *2* | *8* |
| | *Reinforced concrete* | ↓ | ↓ |
| | *Polyester fiberglass reinforced* | ↓ | ↓ |
| *Circling barriers* | *Presence* | *1.2* | *1.7* |

*Table 12. Variables that did not showed evidence to influence pipe's failure probability*

| ***Variable/Parameter*** |
|---|
| *Pipe's diameter* |
| *Pipe's length* |
| *Pipe's age* |
| *Pipe-tree distance* |
| *Water table depth* |
| *Cumulative precipitation (2006)* |
| *Exhibits roots* |

The three models showed evidence that the stoneware failed more than the concrete (which is the most common material in the sewer system), the odds ratio obtained by the logit model was in average 2 and 8 for sediment-related failures and structural failures respectively. This means that the odds that stoneware pipes fail are 2 and 8 times more respectively. Similarly, consistent results were found for reinforced concrete pipes and polyester fiberglass reinforced, whose average OR where 0.4 and 0.2 (for sediment- related and structural failures respectively) in relation with concrete pipes. On the other hand, pipe's diameter length, age and distance from the tree showed OR next to 1, meaning they do not affect the probability of pipe failure. The same conclusions were drawn for the water table depth, precipitation and roots exhibition.

# CONCLUSIONS

Preliminary linear regression models made evident the need to include more variables and to outline new and more complex patterns to relate the available information. Based on these results, new analyses were proposed trying to lead the research towards a robust model that may allow the understanding of the interaction among tree roots and waste water pipes.

This work has allowed to develop three models that relates spatially and differently the urban tree inventory, the failures data base and the pipe's information set; with three different statistical analysis: linear regressions, logit and poisson models. Some tree species showed different results regarding the same variables; however, some results were consistent for all spatial models and statistical models. Precipitation and water table depth didn't show statistical evidence to assure it affects positively or negatively the occurrence of sediment-related or structural failures, which evidence that environmental variables may not have an important effect on tree roots and pipes interaction.

A very short percentage of the species under study had statistical evidence to support the hypothesis that they may have an effect on the occurrence of failures. Species such as some Ficus (e.g. Caucho benjamín and Caucho de la india) showed evidence to be related with sewer failures. But others, such as Eucalyptus (Eucalipto plateado) and some Pinus were not identified as prone to cause root intrusion in the model results.

Some materials such as stoneware and brick showed to be more related to the presence of failures, with odds higher than one. This findings were also stayed in previous studies that pointed out vitrous clay as more prone to present root intrusion in contrast with concrete and PVC (Pohls et. al., 2002; Wong et. al. 1988). In the other hand, materials such as reinforced concrete and polyester fiberglass reinforced, proved to have less incidence of failures in contrast to concrete, analysis with such specific materials, after an exhaustive search, were not found in literature review. The study showed that circling barriers have a counterintuitive effect. The calculated odds ratio showed that instead of preventing root intrusion events, they make more vulnerable the pipe in the tree surroundings. This may be explained by the fact that circling barriers prevent root growth in a lateral plane, directing root's growth towards higher depths and as a consequence, making more vulnerable sewer pipes.

Some pipe's characteristics such as diameter, length and age presented the same odds and IRR to evidence failures. Moreover, its coefficients in linear regression models were near to cero, meaning they have no effect in the response variable. Previous studies carried out show that some specific pipe diameters are more affected by root intrusion than others (Pohls et. al., 2002). Also, as the number of joints increments when pipes length is shorter, theory state that a higher number of joints makes more vulnerable the system (Ridgers et. al., 2006). Similarly, Pohls et. al., 2002 states that pipes older than 30 years are more prone to present root intrusion events. This deviations from the literature review may be explain by the fact that the interaction among froots and pipes is so complex that can be hardly explained by a short list of variables. Construction quality, soil compaction, soil type and soil use may influence strongly the interaction, hiding the effect of other variables. It may also be noted that tree species are specific from the case of study and, moreover, even the same specie shows different characteristics according to the site and the nearby environment.

As a first approach, this study have highlighted the importance to make *in-situ* studies for Bogota city; because of the difficulty to extrapolate results from literature. The information provided by this study is especially important for the decision making process for tree planting authorities and water utility by i) understanding which tree species should not be planted on sewer system surroundings ii) which materials are more resistant to root intrusion, iii) reconsidering the need of using circling barriers and iv) implementing tree species and pipe materials as a design parameter in the prioritization of pipes that need preventive maintenance.

# FUTURE WORK

Future efforts to understand the interaction among tree roots and pipes should be addressed towards the understanding of the role of joins and soil type. It's also recommended to use tree growth projections in order to determine tree characteristics in time and relate them with historical failures database.

It's recommended also to evaluate the effect of nearby trees (of the same and other specie) for each tree observation and to develop regressions to quantify the effect of native and non-native species.

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# ANNEX 1

| Specie | Subspecies | Specie | Subspecies |
|---|---|---|---|
| *Acacia* | *Acacia Baracatinga* | Eucalipto | *Eucalipto Plateado* |
| | *Acacia Japonesa* | | *Eucalipto de flor (Citrinuss)* |
| | *Acacia Morada* | | *Eucalipto Manchado (Maculata)* |
| | *Acacia Negra* | | *Eucalipto (Camaldulensis)* |
| | *Acacia Blanca* | | *Eucalipto (Viminalis)* |
| | *Acacia de Jardín* | | *Eucalipto Cinirea* |
| *Cajeto* | *Cajeto* | *Guayacán de Manizales* | Guayacán de Manizales |
| *Caucho* | *Ficus retusa* | *Liquidámbar* | Liquidámbar |
| | *Caucho lira* | *Magnolio* | Magnolio |
| | *Caucho Benjamin* | *Pino* | *Pino Hayuelo* |
| | *Caucho de la India* | | *Pino Candelabro* |
| | *Caucho Sabanero* | | *Pino Pátula* |
| | *Caucho Tequendama* | | *Pino Montezuma* |
| *Cerezos* | Cerezo,capuli | | *Pino Romerón* |
| | Cerezo, ciruelo | | *Pino Colombiano* |
| *Chicalá* | *Chicalá Flor Amarillo* | | *Pino Azul* |
| | *Chicalá Rosado* | | *Pino Australiano* |
| *Ciprés* | *Ciprés juniperus* | | *Pino Libro* |
| | *Ciprés Italiano* | | *Pino Pinaster* |
| | *Ciprés Japonés* | *Roble* | Roble |
| | *Ciprés Pino (lusitánica)* | | Roble Australiano |
| | *Ciprés (Macrocarpa)* | *Sangregado* | *Sangregado Bogotensis* |
| *Cucharo* | Cucharo | | *Sangregado Magdalensis* |
| *Eucalipto* | *Eucalipto Común* | *Sauce* | *Sauce Llorón* |
| | *Eucalipto Pomarroso* | | Sauce |
| | *Eucalipto Blanco* | *Urapán* | Urapán |

*Legend*

| | ***Root intrusion level*** |
|---|---|
| | High |
| | Medium |
| | Low |

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