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ABSTRACT. Corruption has pervasive effects on economic development and the well-being of the population. Despite being crucial and necessary, fighting corruption is not an easy task because it is a difficult phenomenon to measure and detect. However, recent advances in the field of artificial intelligence may help in this quest. In this article, we propose the use of machine learning models to predict municipality-level corruption in a developing country. Using data from disciplinary prosecutions conducted by an anti-corruption agency in Colombia, we trained four canonical models (Random Forests, Gradient Boosting Machine, Lasso, and Neural Networks), and ensemble their predictions, to predict whether or not a mayor will commit acts of corruption. Our models achieve acceptable levels of performance, based on metrics such as the precision and the area under the ROC curve, demonstrating that these tools are useful in predicting where misbehavior is most likely to occur. Moreover, our feature-importance analysis shows us which groups of variables are most important upon predicting corruption.

POLICY SIGNIFICANCE: Resources to combat corruption are often scarce. While tools such as audits have proven effective in some contexts, they are often costly and difficult to scale and sustain. Therefore, anticipating, with a certain level of precision, where politicians are most likely to misbehave is key in the fight against this problem. Using data from Colombian municipalities, our approach shows how governments can use artificial intelligence tools to predict where irregularities are most likely to occur. This setup also allows us to identify the features with the greatest predictive power to anticipate where misconduct will occur, which is useful for discussions on institutional reform to curb corruption.

KEYWORDS: Prediction, Corruption, Machine Learning, Colombia

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1. INTRODUCTION

Corruption, the misuse of public office for private gain (Svensson, 2005), has pervasive consequences on the development of countries and the well-being of the population. Corruption affects governments' abilities to collect taxes (Olken and Pande, 2012), provide public goods and services (Olken, 2007), and correct negative externalities (Bertrand et al., 2007). The private sector is also affected by malfeasance, as firms' production choices and investment decisions are less efficient as a consequence of the higher levels of uncertainty generated by corruption (Sequeira and Djankov, 2014). Moreover, corruption acts as a barrier to entry for new firms, thus limiting market competition (Colonnelli and Prem, 2022). Not surprisingly, corrupt countries tend to have lower levels of GDP per capita, worse indicators of human capital, and lower levels of trade openness and political freedom (Svensson, 2005).

Despite its relevance, fighting corruption is tough, in part because it is difficult to measure and detect. Traditionally, most corruption measures have been based on perception surveys, in which key actors, such as businessmen or journalists, are asked their opinion regarding how corrupt a country is. These measures, some of which are still in force, were largely developed to make comparisons between countries.¹ However, comparisons within countries, for example between cities, are also important as they can determine how resources need to be allocated in the fight against corruption. In recent years, there has been notable progress towards the use of more objective and granular indicators of malfeasance. Some of these measures use, as a source of information, either the data contained in the public procurement platforms of each country, or the results of the audits carried out by the anti-corruption agencies.

In fact, the evidence suggests that top-down accountability, whose main tool are audits conducted by high-level agencies, is an effective tool in the fight against corruption (Olken, 2007; Ferraz and Finan, 2008, 2011) and can have positive effects on economic performance (Colonnelli and Prem, 2022; Colonnelli et al., 2022). But audits are a costly and scarce resource, in terms of time, money, and human capital. They cannot be carried out all the time everywhere, therefore they need to be assigned efficiently if what is sought is to maximize their effectiveness. In this context, recent advances in the field of artificial intelligence can be useful, since they allow us to anticipate where corruption is most likely to occur. Gallego et al. (2021b) and Decarolis and Giorgiantonio (2020) apply these tools to predict malfeasance in public procurement at the contract level in Colombia and Italy, respectively; Colonnelli et al. (2020a) and de Blasio et al. (2020) use them to develop corruption indicators at the municipal level in Brazil and Italy, respectively; while Salles and Delles (2020) follow a cross-country approach.

¹See, for instance, Transparency International's *Annual Corruption Perception Index* or the World Bank's *Control of Corruption Index*.

In this article, we train a set of machine learning models to predict corruption at the municipality level in Colombia.² For this purpose, we use the results of the prosecutions for disciplinary offenses carried out by the Office of the Inspector General against mayors of the country's municipalities, for the 2008-2011 and 2012-2015 mayoral periods. Using this indicator as the outcome variable, we train four canonical machine learning models—Random Forests, Gradient Boosting Machine, Lasso and Neural Networks—and ensemble their predictions using the Super Learner approach (Polley et al., 2011). These models are fed by 147 municipality-level predictors, which in turn, are grouped into 10 categories of interest that allow us to understand what are the most important predictors of corruption.

Our results show, on the first place, that misconduct at the municipality level in Colombia can be predicted with tolerable levels of precision. The performance of our models is acceptable, reaching levels of precision of 84% and an area under the ROC curve (AUC) of 0.71, two metrics commonly used in the literature to evaluate algorithms. Secondly, our feature importance analysis allows us to understand which characteristics have the greatest predictive power when forecasting corruption. The results show that, in the Colombian case, variables associated with the development of the financial sector and human capital have the greatest predictive power. Variables associated with the public sector, local politics, or crime have a lower weight, despite being frequently associated with corruption. Finally, characteristics typically related with the Colombian context, such as armed conflict, illicit activities, or dependence on natural resources, have the least predictive weight.

We consider that the construction of this type of indicators, based on observable characteristics of the municipalities and using cutting-edge artificial intelligence models, represents an important tool in the fight against corruption. In fact, in a recent application in the context of the economic and health crisis caused by the COVID-19 pandemic in Colombia, Gallego et al. (2020b) finds that municipalities with a higher risk of corruption according to a predicted index based on a machine learning model, show a greater increase in the use of discretionary (non-competitive) contracts to respond to the emergency. This result is consistent with the fact that several mayors have been investigated and convicted of misusing resources in the midst of the emergency, demonstrating that corruption indexes based on machine learning models can indeed serve to anticipate in which places misconduct is more likely to occur.

From a public policy perspective, this work represents an important contribution as it illustrates how artificial intelligence can be used to allocate scarce resources. Anti-corruption audits are effective but expensive, so predicting where they will have the greatest impact may help increase government efficiency. Critical events, such as the COVID-19 pandemic, in which governments have to spend a lot in a short time, create opportunities for corruption

²Municipalities are the third administrative layer in Colombia, equivalent to counties in the U.S.

(Gallego et al., 2021a). Therefore, these types of tools are crucial for governments to respond quickly to the transparency challenges created by these events. Additionally, compared to other studies that predict malfeasance at the contract level (e.g. Gallego et al. (2021b); Decarolis and Giorgiantonio (2020)), in this article, we focus on the municipal level, which is important given the way audits are allocated in some countries. Colonnelli et al. (2020a) and de Blasio et al. (2020) also predict at the municipal level for Brazil and Italy, respectively. The advantage of our study is that by focusing on a country like Colombia, we can analyze the role played by key variables in this context, such as those related to the armed conflict, drug trafficking, or certain types of natural resources.

2. CONTEXT AND DATA

2.1. Context. Colombia is considered a country highly affected by corruption. It is ranked 96, out of 180 countries, in Transparency International's Annual Corruption Perception Index. Furthermore, a recent opinion poll reveals that 78% of the population considers that corruption is getting worse in the country, and 29% think that this is the worst problem in Colombia. A recent report on this phenomenon, based on national and regional press reports, found that 69% of corruption cases in the country are associated with the municipal order (Transparencia por Colombia, 2019).³ This is particularly serious, considering that since the decentralization process that began to consolidate in the 1990s, mayors began to decide on increasingly larger fractions of the public budget.⁴ In fact, mayors are in charge of providing basic public services in important areas such as education, health, drinking water, and sanitation.

The Office of the Inspector General (PGN for its Spanish acronym) is the autonomous agency in charge of monitoring the behavior of public officials so that their actions comply with the current disciplinary code. The Inspector General is elected for four years by the Senate from a list proposed by the President, the Supreme Court of Justice, and the Council of State. The PGN is empowered to initiate, carry out, and rule on investigations conducted against public servants due to disciplinary offenses (Cetina et al., 2020). These investigations may be induced by press news, its own audits, reports from other agencies, or tip-offs (Martinez, 2019). After starting a process, the officials assigned to the case verify and analyze the information received, assess the facts and the responsibility of the people involved, and if they find sufficient evidence, file charges. In this way, the PGN is independent of the three branches of government in Colombia. However, unlike in other countries, the assignment of anti-corruption audits is not random.

³In contrast to 25% at the departmental level and 6% at the national level.

⁴In Colombia, there are 1,100 municipalities and the mayors are their main authority. Currently, they are elected to four-year terms, with no possibility of immediate reelection.

Investigations can end in sanctions and removals from office of members of the executive, including the mayors, whenever misconduct is proved. According to [Transparencia por Colombia \(2019\)](#), the four most committed crimes in recent years are embezzlement (18%), wrongful awarding and signing of contracts (13%), falsification of a public document (12%), and conspiracy to commit a crime (11%). Just to give an example, the case of Samuel Moreno, elected mayor of Bogota for the 2008-2012 period, is quite illustrative. Moreno was suspended and removed from office by the Office of the Inspector General on 2012, accused of corruption in public procurement, in particular for the construction of a public transport trunk line. Moreno is currently in prison, serving an 30-year sentence for these crimes.⁵

2.2. Measuring Corruption. Measuring corruption is challenging ([Olken, 2007](#); [Olken and Pande, 2012](#)). More so measuring corruption for all the districts of a particular country.⁶ Rather than relying on perceptions of citizens or key actors—a common approach to measure corruption championed by international organizations—we follow [Gallego et al. \(2021b\)](#) and [Colonnelli et al. \(2020a\)](#) and use a machine learning approach to predict corruption based on factual corruption detections and observable characteristics of municipalities.

Using information from the Office of the Inspector General of Colombia and originally collected by [Martinez \(2019\)](#), we construct a dummy variable indicating if the mayor of each municipality was prosecuted by this anticorruption agency in the 2008-2011 or 2012-2015 mayoral periods. We define this measure as our outcome variable and combine it with a large set of municipal features to train four machine learning models: Random Forests, Gradient Boosting Machine, Lasso, and Neural Networks.

Note that our outcome variable corresponds to PGN prosecutions for violations of the disciplinary code. It is important to highlight several aspects of this measure. First, according to [Martinez \(2019\)](#), in 95% of the cases in his database where the outcome of the prosecution is observed, the investigation leads to a disciplinary sanction. Therefore, this measure is really capturing instances of misbehavior on the part of public servants, mostly mayors (70%). Second, unfortunately, with the information available, we cannot identify which of the investigations correspond to major offenses or minor ones. However, at the municipal level and for the period of interest of this study, the correlation between having an official found guilty and having one removed from office is positive, highly significant, and large in magnitude (Pearson $\rho=0.73$). Therefore, as this is a purely predictive exercise, this high correlation implies that detecting places where an official is likely to be found guilty means it is also highly likely that an official committed a serious offense to the code. Nonetheless, an

⁵See <https://www.eltiempo.com/justicia/delitos/cuantos-anos-de-carcel-terminara-pagando-samuel-moreno-420648> (last accessed August 24th, 2021).

⁶[Ferraz and Finan \(2008\)](#) and subsequent papers by the same authors measure corruption using the results of public audits in Brazil, that are only available for a subset of municipalities. In the case of Colombia, [Transparencia por Colombia \(2017\)](#) produced an index that focused on 28 department capitals.

important caveat of our analysis is that although the dependent variable certainly captures the misconduct of public servants, it does not always measure severe acts of corruption.

Finally, this measure can also suffer from what the machine learning literature has called the *selective labels problem*. As we described before, the decision of when and who to investigate is up to the PGN, with no randomness in the process. Therefore, this decision is not free from bias since investigators could go after cases in which more resources are involved, they could be intimidated or bribed by illegal actors, or they could simply make errors of judgment. Therefore, the observed outcomes are not necessarily a random sample of the population, which makes the predictive exercise more complicated.⁷ However, it is reassuring that the results presented below, both in terms of the performance of the models and the feature importance, are not substantially different from those of Colonnelli et al. (2020a), who use data from proven cases of corruption detected after random audits in Brazil. An interesting avenue for future research—which is outside the scope of this study—is to use the *contraction* method proposed by Lakkaraju et al. (2017), which “facilitates effective evaluation of predictive models even in the presence of unmeasured confounders (unobservables) which influence both human decisions and the resulting outcomes”. In any case, we acknowledge that these predictive exercises will be more accurate when audits are randomly assigned, which in itself is an important policy recommendation.

2.3. Covariates. We use a total of 147 municipality-level predictors, grouped into ten categories and measured based on the electoral period before the time at which the outcome was measured. The categories are: financial sector, conflict, crime, human capital, local politics, public sector, local demographics, economic activity, illegal activity, and natural resources. The financial sector category includes per capita measures of financial sector employees, bank deposits, bank credits, housing credits, bank offices, among others. Conflict and crime variables include guerrilla and paramilitary presence and attacks indicators, demobilized combatants, kidnappings, homicides, robberies, etc. The human capital dimension includes several educational features.

Local politics refers to electoral variables such as the number of candidates, margin of victory, voter turnout, among others. The public sector dimension includes judiciary indicators, expenditures, transfers, and revenues, and state capacity indices. Local demographics refer to population, density, rurality, inequality, child development, access to public services, etc. In the case of economic activity, we include GDP measures for different sectors and nighttime lights. The illegal activity dimension includes variables related to coca production and illegal mining. Finally, natural resources refers to features describing the oil, gold, and

⁷It could even be concluded that more than measuring the probability of corruption, our outcome variable measures the probability of being investigated.

palm sectors plus some measures of deforestation. Table A1 in the appendix includes the complete list of covariates used to train the models.

3. MACHINE LEARNING MODELS

In this section we describe the machine learning models used to predict corruption as well as the training procedure and the different measures we use to assess the performance of the different models.

3.1. Models. In order to predict municipality-level corruption, we train a set of popular machine learning models, which include Random Forests, Gradient Boosting, Neural Networks, and Lasso. Each of these models has their own weaknesses and strengths, and therefore we also rely on an ensemble model that combines the predictive power of all individual models to optimize the overall performance (Friedman et al., 2001). We ultimately allow the data to inform which of the models is best suited for this application based on their out-of-sample performance.

3.1.1. Lasso. The Lasso regression, first developed by Tibshirani (1996), is similar to a logistic regression model, but adds a penalization term based on the sum of the absolute values of the coefficients and a penalization term based on the sum of the square of the parameters. By adding these penalization terms, the parameters of the model are shrunk towards zero, leading to a more parsimonious model than the logistic regression. In this way, we end up with a simple and less prone to over-fitting model. The tuning parameter in the cross-validation are the weight of the penalization terms in the objective function (λ) and the relative weight of the absolute sum of coefficients (α) as the penalization term.

3.1.2. Random Forests. Random Forests are ensembles of many decision trees, where each one of them is a sequence of rules that divides the sample into leaves, i.e. sub-groups, based on certain variable cutoffs. The prediction for each leaf, in the case of a classification task, is the most common outcome for the trained observations on that leaf. The trees are fit with the aim of maximizing the information gain of the resulting partitions of the data. In the case of Random Forests, each tree is constructed by sampling a random subset of the training data and a random subset of the predictors. Each of these trees ends up generating a prediction, and the overall prediction of the Random Forest is the average (or the majority) of the predictions among all trees. In this application, we keep fixed the number of fitted trees (500) and use cross-validation to determine the optimal number of features available in every node.⁸

⁸See Marsland (2011) chapter 13 for more details.

3.1.3. *Gradient Boosting Machine.* Gradient Boosting Machines (GBM) are ensembles of weak learners, in this case, decision trees. Under boosting, classification algorithms are sequentially applied to a reweighted version of the training data (Friedman et al., 2000). GBM is a variant of Random Forests, in which trees are not fitted randomly nor independently. Instead, each tree is fitted sequentially to the full dataset, in such a way that the weaknesses of trees are identified by using gradients in the loss function, allowing subsequent predictors to learn from the mistakes of the previous ones. In other words, a gradient descent procedure is used to minimize the loss when adding new trees. As opposed to Random Forests, in this case observations are not selected via bootstrapping, but as a function of past errors. By doing this each new tree offers a slight improvement of the model (Freund et al., 1999). In our models, we keep fixed the learning rate (shrinkage parameter) and the minimum number of observations in the terminal nodes to avoid overfitting, and use our cross-validation procedure to determine the optimal number of trees and the interaction depth.

3.1.4. *Neural Networks.* Neural networks capture the relationship between input and output signals through models that mimic the way biological brains work. These models are composed of three basic elements: an activation function, that for each neuron, transforms the weighted average of input signals (predictors) into an output signal; a network topology, which is composed by the number of neurons, layers, and connections used by the model; and a training algorithm, which determines the way in which connection weights are set with the task of activating or not neurons as a function of the input signals. This process determines the final prediction of the model. The optimization problem seeks to find the optimal weights of the input signals for each node. In our analysis, we keep fixed a logistic activation function and use cross-validation to determine the optimal number of units in the hidden layer (size) and the regularization parameter (decay).⁹

3.1.5. *Super Learner Ensemble.* Ensembles are collections of models which are grouped to each other, in order to give a final prediction. It is usually the case that ensembles—as they result from the combination of different models—perform better than their individual components. For our analysis, we use the Super Learner ensemble method developed by Polley et al. (2011). This model aims to find an optimal combination of individual models by minimizing the cross-validated out-of-bag risk of these predictions. Van der Laan et al. (2007) show that this ensemble model performs asymptotically as well as the best possible weighted combination of its constituent algorithms. Finally, we also use the Super Learner model not only to stack the individual predictions, but also to test for the relative importance of different groups of variables to predict politician's misconduct.

⁹See Marsland (2011) chapter 3 for more details.

3.2. Training and Testing. We use an indicator variable for politician's misconduct in mayoral term t as our variable of interest and all the predictors are measured as averages within the politician term. In this way, we end up with a cross-sectional dataset with all the municipalities for the mayoral periods 2008-2011 and 2012-2015. In order to train our models, we conduct the following steps:

- (1) We divide our dataset into a training set that uses 70% of the data and a testing set that uses 30%.
- (2) In our training set we perform a 5-fold cross-validation procedure in order to train our models and choose the optimal combination of parameters. This method divides the training set into five different equal size samples at random. Then, a model is fit in four subsamples and then test it in the remaining one. We then repeat this procedure for each of the five subsamples, so each one of them end up being a validation set, and for each of the values of the tuning parameter grid of each model. Finally, the best performing parameters are chosen.
- (3) We repeat the previous step 10 times with different random partitions. In this way we are able to obtain 10 "optimal parameters." Then we use as our optimal parameter the average of them. In the case of integer parameters we round it to the closest integer.
- (4) Based on these optimal parameters we assess the performance of our models in the test set that has never been used for training purposes.

We standardize the data by the mean and standard deviation. Table 1 shows the optimal parameters from our training procedure for each of our models.

3.3. Assessing Models' Performance. Once we have calibrated our model following the procedure explained above, we proceed to compare the performance of the different models using the test set. Our first performance measure of interest is the area under the ROC (Receiver Operating Characteristic) curve (AUC). This measure captures the trade-off between the true positive rate and false positive rate, as we vary the discrimination threshold. It can also be interpreted as the probability that, if we randomly select two observations, they will be correctly ordered in their predicted risk of corruption, i.e. the probability that the municipality at a greater risk for corruption is assigned a higher probability of corruption. We complement this measure with each model's level of *accuracy*, which is defined as the proportion of municipalities correctly predicted as corrupt; model's *sensitivity* which is the proportion of actual positives identified correctly (true positives over true positives plus false negatives); model's *precision* which is the proportion of correctly identified positives (true positives over true positives plus false positives), and models' *specificity* which is the proportion of actual negatives identified correctly (true negatives over true negatives plus false positives).

TABLE 1. Model's Parameters

Model	Optimal parameters
Lasso	λ : 1 α : 0.011
Random Forest	Trees: 500 Mtry: 4
Gradient Boosting	Trees: 200 Depth: 9 Shrinkage: 0.01 Min obs: 10
Neural Networks	Size: 1 Decay: 0.9
Ensemble Weights	Lasso: 0.53 Random Forest: 0.47 Gradient Boosting: 0 Neural Networks: 0

Notes: This table presents the optimal parameters for each of the prediction models we implement after the training procedure described in section 3.2.

3.4. Identifying Best Predictors. We begin by assessing the individual municipality characteristics that best predict corruption. In the case of tree-based models, importance is measured as the information gain, achieved when splitting on each variable. In this case importance is measured on a scale from 0 to 100, where 100 is value for the most important predictor and the rest of the variable's information gain is expressed relative to the variable with the highest one. For the Lasso model the importance is measured by the estimated coefficients, where larger coefficients (in absolute value) correspond to higher importance. Finally for Neural Networks, importance is determined by the weights that connect neurons within the network.

We then move to the analysis of the predictive power of subgroups of related municipality characteristics in order to understand which categories matter the most. It could be the case that some groups do not have one particular variable that highly predicts corruption, but that the group as whole has a high predictive power. To do this, we estimate models including one category at the time (i.e. excluding all covariates that are not part of it) and compute the resulting AUC for the group. Then, we are able to rank them according to their AUC, and compare the computed AUC with a 50% level, which corresponds to the AUC of a random prediction "model." In this case, the group that increases the AUC by

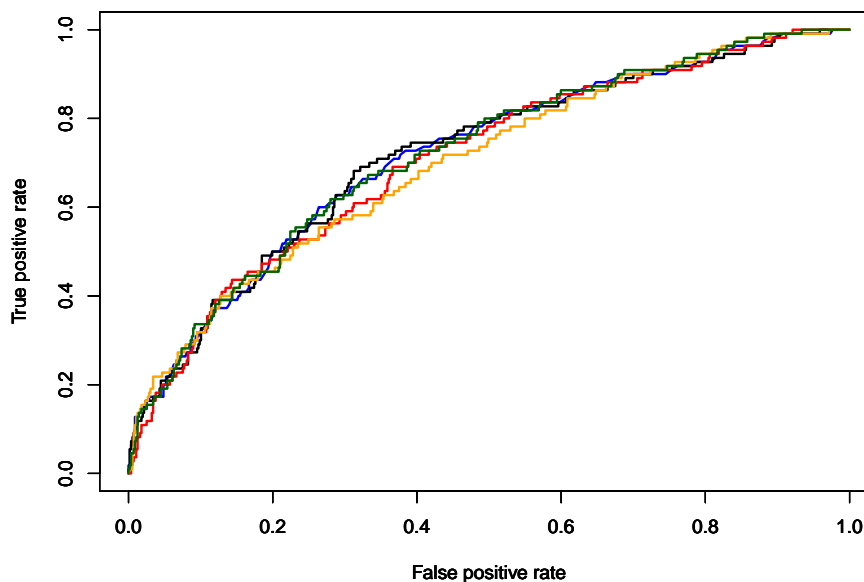
itself the most is the model with the highest level of predictive power. Finally, we assess the statistical difference in the predictive power between groups by computing confidence intervals at a 95% confidence level. We do this using a bootstrap procedure over the test set and computing the AUC for each sample.

4. FINDINGS

In this section, we present the main results of our analysis. First, we focus on the overall performance of the predictive models. Then, we identify the best individual and group predictors and their link to the corruption literature.

4.1. Models' Performance and the Predictability of Mayors' Misconduct. Figure 1 plots the ROC curves for each of the four models and for the ensemble. There are several aspects to highlight: first, all the curves are far enough away from the 45-degree curve, which would correspond to a naive classifier that generates a false positive for each true positive. Second, the Neural Network achieves the worst performance of all according to this metric, which explains why it is not used in the ensemble, as shown in Table 1. Finally, the performance of the remaining models, in regards to the area under the ROC curve (AUC), is similar and acceptable, without being outstanding.

FIGURE 1. ROC curve



Notes: This figure presents the ROC curves for all our models. In **blue**, we present the ROC curve for the Random Forest model, in **black**, for the Gradient Boosting Machine, in **red**, for Lasso, in **orange**, for Neural Networks, and in **green**, for the Super Learner.

Table 2 corroborates the previous assertion. In terms of the AUC, Random Forest, GBM, and the ensemble achieve the highest performance (0.72), compared to the Neural Network, which achieves the lowest (0.70). Accuracy is similar in all five models, with a hit rate of 84% for Random Forests, GBM, Lasso, and the ensemble, and 81% for the Neural Network. Table 2 reports three additional metrics, sensitivity, specificity, and precision. The metrics suggest that the models tend to predict more false positives, as suggested by the low levels of precision.¹⁰ In sum, although the models do not reach performance levels as high as in other studies,¹¹ an accuracy of 84% and an AUC of 0.72 are still acceptable. Consequently, these models could be used by the authorities to decide where to conduct anti-corruption audits.

TABLE 2. Model Performance

Model	Lasso	Random Forest	Gradient Boosting	Neural Networks	Ensemble
AUC	0.71	0.72	0.72	0.70	0.72
Accuracy	0.84	0.84	0.84	0.81	0.84
Sensitivity	0.50	0.63	0.58	0.39	0.63
Specificity	0.85	0.85	0.85	0.87	0.85
Precision	0.09	0.14	0.13	0.29	0.11

Notes: This table presents the model performance for all our prediction models. *AUC*, *accuracy*, *sensitivity*, *precision*, and *specificity* are defined in section 3.3.

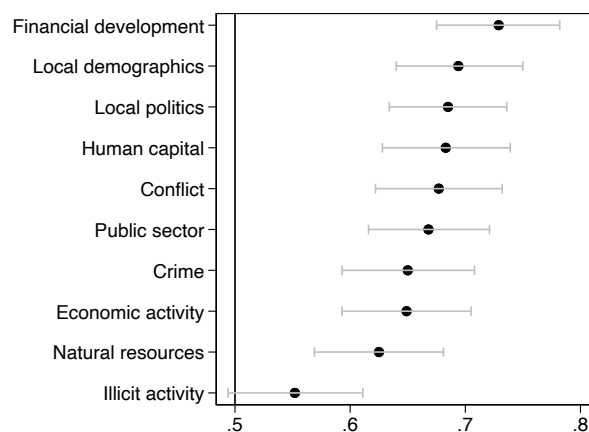
4.2. What Are the Best Predictors of Mayors' Misconduct? The analysis of the features that have the greatest predictive power to anticipate where mayors are most likely to misbehave, is divided into two parts: First, we group the 147 municipality-level characteristics into ten dimensions of interest, to determine how much predictive power each one has. For this, we define the following dimensions: public sector, human capital, economic activity, local demographics, financial development, local politics, natural resources' exposure, illicit activity, crime, and conflict. We then disaggregate the analysis, by studying which individual characteristics, in each model, have the greatest predictive power.

¹⁰This result suggests that the models tend to over predict false positives. From a public policy perspective, the severity of this problem depends on the cost of conducting anti-corruption audits. If they are very expensive, models that generate a high number of false positives are not desirable because many resources would be wasted. On the other hand, if the audits are cheap, it is preferable that the false positives be numerous if that means that there are few false negatives. In any case, the researchers have some level of control over this result because the models can be tuned to optimize metrics such as accuracy.

¹¹Colonnelli et al. (2020a), in the context of Brazilian municipalities, achieve performance metrics usually above 95%. The difference may be that in the Brazilian case, there is better information on the characteristics of the private sector.

Figure 2 depicts the results of the first analysis. Surprisingly, variables associated with financial development rank first, followed by the measures of local demographics, local politics, and human capital. The result is surprising since dimensions that the literature usually associates with corruption, such as those related to the public sector, crime, or conflict, occupy intermediate positions (Rose-Ackerman and Palifka, 2016; Fisman and Golden, 2017). Shaxson (2007), for example, suggests that the resource curse is explained by the higher levels of corruption that exist in countries where these resources are abundant. Other studies suggest that the size and quality of the public sector is a determining factor in the level of corruption (Robinson and Verdier, 2013; Gallego et al., 2020a; Colonnelli et al., 2020b). However, our results challenge all these explanations by suggesting that the main red flags of corruption are in the financial sector (Cooray and Schneider).

FIGURE 2. Group importance



Notes: This figure presents the relative importance of group of covariates as described in 3.4.

Moreover, variables usually associated with the Colombian context, such as those related to the dependence on natural resources and illicit activities, occupy the last places in this ranking, challenging the view that other manifestations of state weakness would predict where corruption is most likely to occur. In sum, these results corroborate what Colonnelli et al. (2020a) finds for Brazil, in the sense that variables associated with the private sector have a preponderant weight when explaining the level of corruption within a country, while the characteristics related to the public sector have less weight. These findings contrast with the great emphasis that is usually given to the public sector and public officials when thinking about anti-corruption reforms (Olken and Pande, 2012).

Finally, Figure 3 illustrates which individual variables have the greatest predictive power for each machine learning model. It is interesting that in three out of four cases, a financial sector variable ranks first: The number of financial sector workers for the Random Forests and the GBM, and the size of the housing credit market in Lasso. Other financial variables

appear consistently in the models, like the number of bank offices.¹² This result reaffirms what was found above, in the sense that the level of development of the financial sector is key to understanding why some places are more corrupt than others.¹³

Delving into why the development of the financial sector is an important predictor of corruption is outside the scope of this study, among other things, because this exercise is purely predictive and not causal. However, we propose a hypothesis: the degree of concentration and competition in the financial sector, reflected in the size of its main players, can determine the levels of rent-seeking, money in politics, and influence in government decisions. Anecdotal evidence from the Colombian case would give suggestive support to this hypothesis. The AVAL group, the leading financial conglomerate in the country, was related to the so-called Lava Jato scandal and the Brazilian multinational Odebrecht. According to judicial investigations, the Brazilian company and officials from the financial group bribed public servants from the Ministry of Transportation in 2009 to be awarded the construction of a major highway in the country.¹⁴

Finally, we would like to underscore one of the main limitations of our analysis. As we said before, the exercise presented here is predictive, but not causal. This fact means that these types of tools inform in what kind of places acts of corruption are more likely to occur (e.g. depending on the development of the financial sector). However, the models hardly shed light on the type of reforms or interventions (in that sector) that would help control corruption. To answer this type of questions, causal inference tools such as randomized controlled trials or quasi-experimental methods are still useful, some of which are strengthened by machine learning, such as the doubly robust models proposed by Belloni et al. (2014).

5. CONCLUSIONS

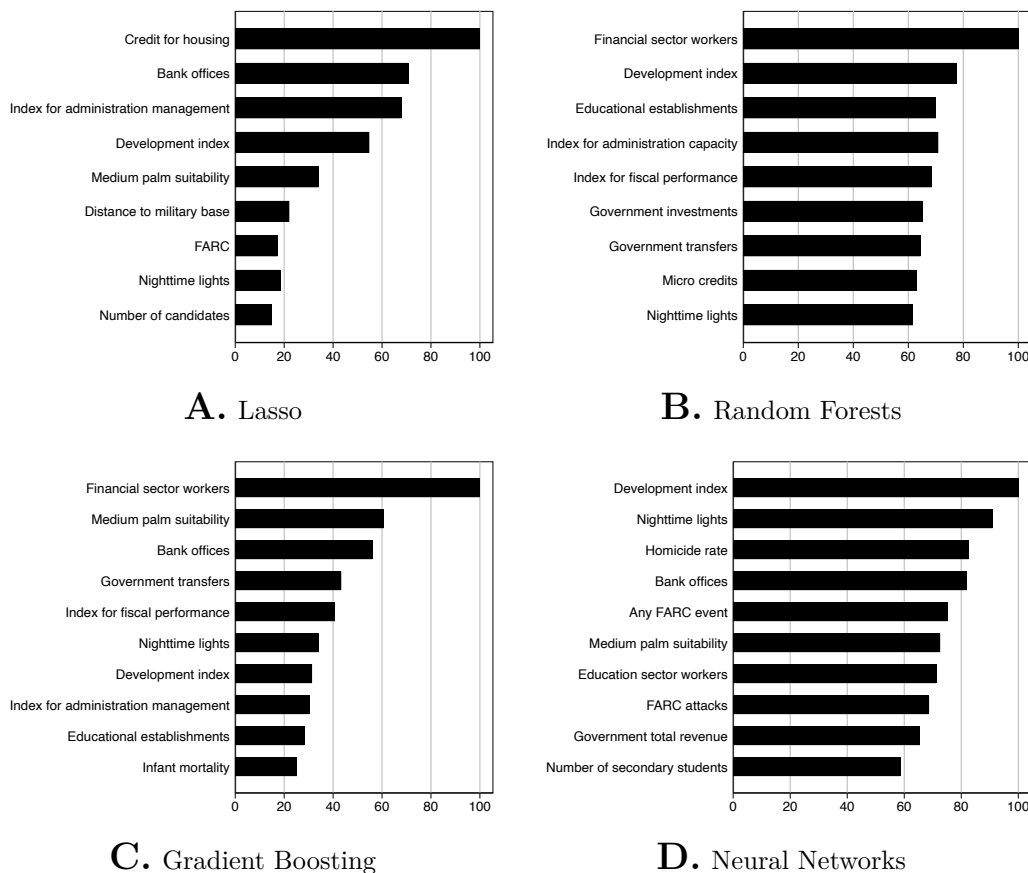
In this article, we propose the use of artificial intelligence tools to predict where rulers are more likely to commit acts of corruption. We apply these methods to the Colombian case, exploiting the fact that municipal mayors manage a significant fraction of public resources and are frequently involved in corruption scandals. Using information from prosecutions conducted by the Office of the Inspector General against these mayors, we trained four canonical machine learning algorithms, and ensemble their predictions, to forecast where there is a greater risk of corruption. The performance of our models is good and allows us to understand what are the features of municipalities that have the greatest predictive power to

¹²Although the set of variables varies from model to model, it is also noteworthy that the municipal development index appears consistently in all cases.

¹³It is important to clarify that these graphs only tell us which variables matter most in each model, but not what is the direction of the relationship. To determine this direction, it is necessary to calculate the *partial dependency plots* of each variable. We omit such graphs to save space, but are available upon request.

¹⁴See <https://colombiareports.com/amp/colombias-prosecution-under-fire-for-absolving-ceo-of-corrupt-banking-giant/>. Last accessed: 8/2/2022.

FIGURE 3. Covariates importance



Notes: This figure presents the relative importance of covariates as described in 3.4.

anticipate where will misconduct occur. Surprisingly, variables associated with the financial sector have the greatest weight, features related with the public sector play a secondary role, while characteristics associated with the armed conflict, illicit activities, and dependence on natural resources have the least predictive power.

From a public policy perspective, we consider these tools to be particularly useful. Anti-corruption audits, carried out by independent agencies, have proven to be efficient in curbing this phenomenon (Olken, 2007; Ferraz and Finan, 2008, 2011) and in improving economic performance (Colonnelli and Prem, 2022). But audits are expensive and therefore a scarce resource. Its use must be optimized so that its effectiveness is the highest. The use of artificial intelligence tools, as illustrated in this article, helps to fulfill this purpose, especially during crises such as pandemics, wars, and natural disasters, in which governments must spend a lot and in a short time, which creates opportunities for corruption.

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DATA AVAILABILITY: The data that support the findings of this study will be openly available upon publication.

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COMPETING INTEREST: Jorge Gallego, Mounu Prem, and Juan Vargas declare none.

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Online Appendix

TABLE A1. Description of Variables

Categories	Source	Variables
Financial sector	SFC	Bank deposits per capita, bank credit per capita, housing credit per capita, micro credit, over population, bank offices per capita, financial sector employees over population, number of credit loans for small rural producers per capita, number of credit loans for middle rural producers per capita.
Conflict	Universidad del Rosario, Ministry of Defense, National Police.	FARC armed attacks per capita, ELN armed attacks per capita, paramilitary groups armed attacks per capita, unknown groups armed attacks per capita, indicator of FARC presence, indicator of ELN presence, indicator of paramilitary groups presence, number of demobilized combatants from other armed groups per capita, number of demobilized combatants from FARC per capita, number of demobilized combatants from ELN per capita, number of demobilized combatants from paramilitary groups per capita, number of demobilized combatants per capita, number of expelled displaced people per capita, number of incoming displaced people per capita.
Crime	DNP Ministry of Defense, National Police.	Number of domestic violence cases per capita, number of guns seizure per capita, number of kidnappings per capita, homicides per capita, number of arrests per capita, number of thefts per capita, number of burglaries per capita, number of motorcycle thefts per capita, number of commercial burglaries per capita, number of bank robberies per capita, number of car thefts per capita, number of total thefts per capita.
Human capital	2005 Census, Ministry of Education,	Literacy rate (Census), average test scores in Spanish and Math for Pruebas Saber 11, number of public schools per capita, number of non-public schools per capita, population of primary school age per capita, population of high school age per capita, number of school officials per capita, number of teachers per capita, number of teachers per capita in rural areas, number of teachers per capita in urban areas, number of students, per capita, number of students per capita in rural areas, number of students per capita in urban areas, number of preschool students per capita, number of primary school students per capita, number of high school students per capita, number of middle school students per capita, number of subsidized students per capita, number of subsidized students per capita in rural areas, number of subsidized students per capita in urban areas.
Local politics	RNEC	Number of candidates, Hirschman-Herfindahl index based on the vote shares, margin of victory between the winner and the runner-up, an indicator for whether mayor's party is the same as the one of the governor, indicator for whether is from the same party as the one of the president, indicator if mayor is from right-wing party, indicator if mayor is from left-wing party, indicator if mayor is from center-wing party.
Public sector	Ministry of Finance and Public Credit, DNP	Procuraduria offices per capita, Fiscalía offices per capita, Judiciary offices per capita, distance in Km to the nearest military base, total expenditures per capita, personnel expenditures per capita, budget deficit per capita, total revenue per capita, Central Government transfers of capital per capita, Central Government current transfers per capita, local taxes revenue per capita, total investment expenditures per capita, Index of fiscal performance, Index of fiscal efficacy, Index of administrative capacity, Index of administrative management.
Local demographics	Ministry of Health, DANE.	Average number of pre-natal visits, share of births with 4 or more pre-natal visits, child mortality rate, child mortality rate caused by malnutrition, total population, Index of local development, population density, Share of population living in rural areas, infant mortality rate, child mortality, underweight births, water service coverage rate, sewer and drainage service coverage rate, GINI coefficient for income distribution.
Economic activity	CEDE, DMSP, NOAA.	Agricultural sector GDP, industrial sector GDP, service sector GDP, GDP per capita, nighttime lights.
Illegal activity	SIMCI National Police	Coca suitability index based on Mejia and Restrepo (2015), dummy from coca suitability index based on Mejia and Restrepo (2015), municipal share of coca crops, plots of coca crops per hectare, municipal share of aerially eradicated coca crops, municipal share of manually eradicated coca crops, indicator of coca crops presence, share of illegally mined area.
Natural resources	Ministry of Agriculture and Rural Development, DNP	Share of deforested area, indicator of low aptitude for palm cultivation, share of low aptitude area for palm cultivation, indicator of medium aptitude for palm cultivation, share of medium aptitude area for palm cultivation, indicator of high aptitude for palm cultivation, share of high aptitude area for palm cultivation, gold production per capita (kg), oil barrels produced per capita.