

Article

Inferring Missing Climate Data for Agricultural Planning Using Bayesian Networks

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Abstract: Climate data availability plays a key role in development processes of policies, services, and planning in the agricultural sector. However, data at the spatial or temporal resolution required is often lacking, or certain values are missing. In this work, we propose to use a Bayesian network approach to generate data for missing variables. As a case study, we use relative humidity, which is an important indicator of land suitability for coffee production. For the model, we first extracted climate data for the variables precipitation, maximum and minimum air temperature, wind speed, solar radiation and relative humidity from the surface reanalysis dataset Climate Forecast System Reanalysis. We then used machine learning algorithms to define the model structure and parameters from the relationships of the variables found in the dataset. Precipitation, maximum and minimum air temperature, wind speed, and solar radiation are then used as proxy variables to infer missing values for monthly relative humidity and relative humidity for the driest month. For this, we used both complete and incomplete initial data. In both scenarios of data availability, the comparison of estimated and measured values of relative humidity shows a high level of agreement. We conclude that using Bayesian Networks is a practical solution to estimate relative humidity for coffee agricultural planning.

Keywords: probabilistic modeling; machine learning; modeling climate information; graphical models; proxy climatic variables; land evaluation; Central America; *Coffea arabica* L.

1. Introduction

Missing data is a major challenge for agricultural planning, reporting and research not only at the level of individual farms, but also at regional, national, or international scales. Incomplete information leads to misrepresentation and bias, but collecting the missing data can be very costly [1,2]. Several procedures have been employed in previous applications to deal with data gaps. For example, the Agricultural Resource Management Survey in the USA uses conditional or national averages with or without outliers [2]. In agricultural research, data gaps have been filled by combining survey and satellite information [3], spatial interpolations [4], introduction of proxy variables [5], and, in the case of climate research, by using the regularized EM algorithm for Gaussian data [6], empirical orthogonal functions [4], grouping methods of data handling [7], and others.

A scarcity of data, data with a high uncertainty attached or inhomogeneous data from different sources is especially prevalent in developing countries. While the procedures described above are mostly suitable for dealing with the problem, their practical implementation in developing countries is often difficult due to a lack of qualified personnel and financial shortfalls [8–10]. For example,

in several Central American countries, the reconstruction of climate variables using interpolation methods was only possible with external funding from the World Bank [10]. To overcome these hurdles, we propose to use a Bayesian network (BN), which is a mathematical model that graphically represents conditional probabilistic dependencies between variables. BNs can deal with uncertainty, missing data, missing (hidden) variables and small datasets; it is possible to learn the graphical structure and the parameters of the model from data, literature, expert knowledge or a combination of all [11–14]. Another practical advantage of using BN is the availability of free software [15,16].

In a BN approach, data can be generated for variables with missing values while maintaining a consistent relationship with other variables in the same dataset [17]. It also allows the user to incorporate the uncertainty surrounding input data by entering a range or distribution of possible values or by using the prior information parameterized in the model when no information is available. Instead of a single, certain value, the output is then the most probable value of the variable of interest with the uncertainty attached [11,14,18]. The Bayesian ability to handle uncertainty in the modeling process is advantageous, considering that uncertain and missing data are common in real-world situations [19], especially when dealing with climate variables and when working in regions without good data coverage [10,20,21].

There are several options in BNs for dealing with missing data: removing the registers with missing values; using mode values in place of the missing values or estimating the missing values based on the values of the other variables in the corresponding register using probabilistic inference [13]. The last option has the advantage that the complete dataset is used, and that specific values are estimated for the missing registers instead of only a measure of central tendency like the average or median. Therefore, in our approach, we estimate the missing values based on proxy variables and probabilistic inference. As a case study, we created a novel Bayesian network model to estimate the relative humidity for Central America and Southern Mexico. In order to build the model, we used machine learning algorithms available in the Bayesian networks approach to define the model's graphical structure and parameters from monthly relative humidity data [18,22,23]. We then applied the model to infer values for relative humidity under two conditions: using a complete set of input information, and incomplete information, where one or two of five proxy variables were unavailable. The second scenario shows the capability of BN models to produce results even when information is missing. In both scenarios, monthly relative humidity and the Relative Humidity of the Driest Month (RHDM) were inferred. RHDM is one of the main variable-indicators to describe the land suitability for *Coffea arabica* L. production [24].

A comparison of BN-estimated and reported values of monthly relative humidity and RHDM shows a high level of agreement between the values. The results also indicate a high level of consistency in the relationship between estimated relative humidity and proxy variables, which is one of the major concerns in modeling climate data. We conclude that the proposed method is a practical solution for estimating relative humidity, as it is based on information that is readily available and does not require high computational resources or technical expertise. Furthermore, estimating climate data for agricultural planning constitutes an important and unexplored domain for the application of probabilistic graphical models, which have only been used in climate science for weather forecasting [25] and to explore the dependencies between climate variables so far [20]. Thus, this study forms an important contribution to the literature of BN applications and offers a valuable tool for coffee planning in Central America.

2. Methods

2.1. Study Region

The study region, consisting of Central America and Southern Mexico, is located in the tropical zone, where the temperature remains relatively constant throughout the year and changes in season are driven by changes in precipitation. The prevalence of high water vapor contents and tropical

temperatures leads to a high relative humidity [26,27]. The climatic conditions are favorable for coffee production, and most countries in the region are recognized for their high-quality coffee and shaded coffee systems [28–32], together producing more than 10% of the total global coffee supply [33,34]. However, projections of climate change show that the region is likely to experience severe alterations in climate in the future, which may negatively impact coffee production [35–37].

2.2. Relative Humidity

Relative humidity describes the water content in the air [38] and is normally calculated from the ratio between the saturation vapor pressure and the vapor pressure at a specific temperature [39,40]. Relative humidity has been identified as a key factor for coffee quality during the postharvest-storage [41,42] and as an agroecological variable that influences the suitability of a site for coffee production [24,43]. For example, values of RHDM between 50–60% are considered optimal, and values below 20% or above 80% as suboptimal for coffee cultivation [24]. Measurements of relative humidity are done using hygrometers in weather stations; however, this type of measurement is more expensive than measuring temperature or precipitation and therefore done far less frequently. To close the data gap, the development of modeling tools to estimate humidity based on other measured variables is a feasible strategy [26,44]. In this study, we model the variable monthly relative humidity and relative humidity of the driest month, i.e., the month with the lowest precipitation.

2.3. Data

Variables experimentally observed or produced by reanalyses retain consistency among themselves. In our approach, we exploit this correlation to build and parameterize a Bayesian network model for inferring missing values for the relative humidity values from other climate variables. As a data source, we use the surface reanalysis dataset Climate Forecast System Reanalysis (CFSR) [45,46]. CFSR¹ includes daily values for the variables precipitation (mm), air temperature (°C, minimum and maximum at 2 m), wind speed (m/s, at 10 m), surface solar radiation (MJ/m²) and relative humidity (% , at 2 m). The spatial resolution is 38 km × 38 km per pixel and data are available from 1979 to 2014.

We downloaded a set of daily data of all variables, covering Central America and Southern Mexico (a total of 855 pixels) for the years 1979 to 2000. From this dataset, a monthly subset MRH was created by aggregating the daily to monthly data for each year and pixel ($n = 225,720$). Then, a second subset RHDM was created by extracting the data (cases) of all the variables for the driest months of each year ($n = 18,810$). Summary statistics for the variables of both datasets were calculated (Table A1): The data distribution for humidity is different in both datasets, with $\mu = 77.79$ and 69.13, and $\sigma = 9.66$ and 9.08 for the MRH and RDHM datasets, respectively, and in the RDHM dataset, the shape of the humidity distribution is more skewed to the left (Figure 1). The distribution of precipitation also differs markedly between both datasets ($\mu = 8.13$ and 1.05, and $\sigma = 8.38$ and 1.79 for MRH and RDHM datasets, respectively), whereas only minor difference can be found for solar radiation, maximum and minimum temperature, and wind speed.

¹ <https://globalweather.tamu.edu/>

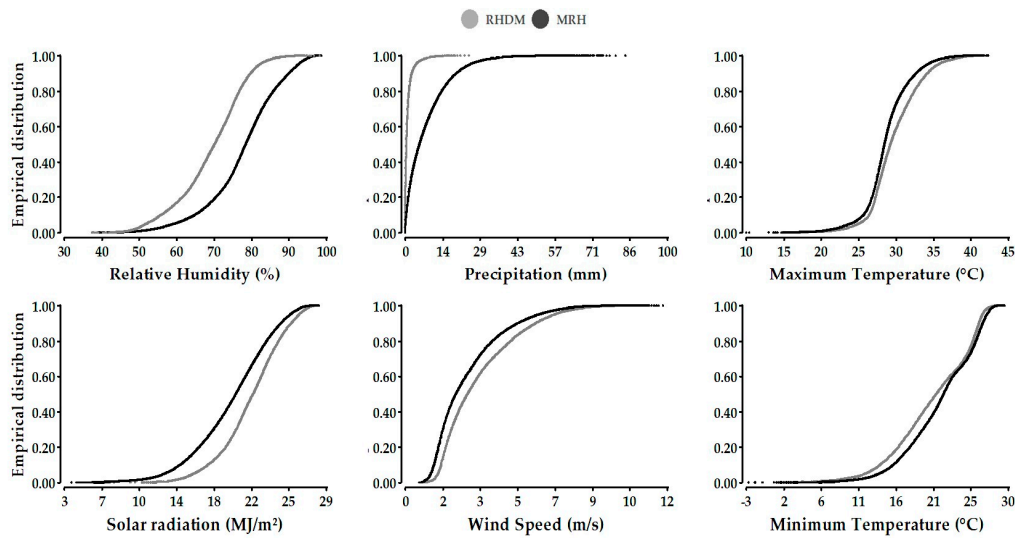


Figure 1. Empirical distributions of monthly relative humidity, precipitation, maximum and minimum temperature, solar radiation and wind speed from the datasets MRH and RHDM ($n = 225,270$ and $18,810$, respectively). MRH: Monthly Relative Humidity; RHDM: Relative Humidity of the Driest Month.

2.4. Variable Selection

An exploratory analysis using principal components was done to identify which variables should be included in the model. For this, the complete dataset MRH was used ($n = 225,270$). The two first principal components explained 91.7% of the data variability (PC1 = 75.5% and PC2 = 16.2%) (Figure 2). Relative humidity has a positive correlation to precipitation (PRCP), and a negative one to TMAX and solar radiation (Solar) (PC1). Under intermediate conditions of precipitation and solar radiation, wind and TMIN have a major influence on the range of relative humidity (65–85%, PC2). With the exception of TMAX, relative humidity has a non-linear relationship with the proxy variables (Figure A1). Since all proxy variables thus influence relative humidity in different situations, we included all in the model.

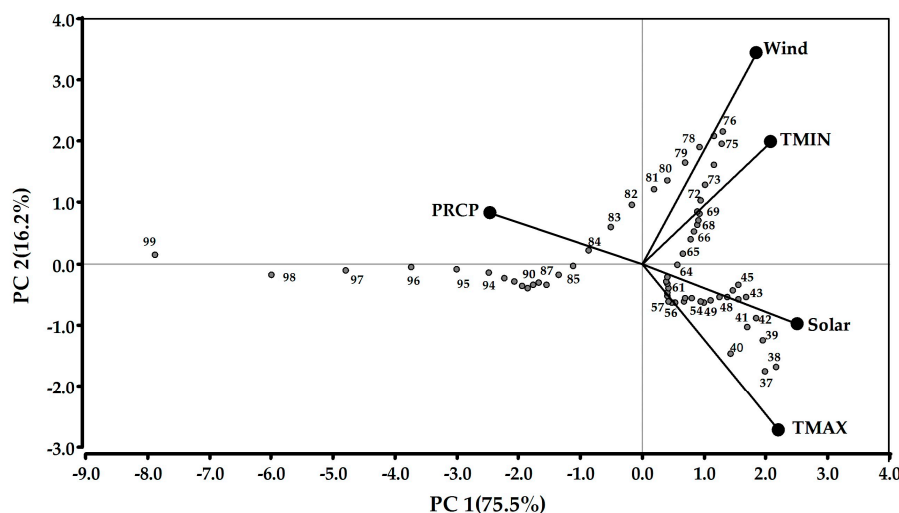


Figure 2. Principal component analysis including precipitation (PRCP), maximum temperature (TMAX), minimum temperature (TMIN), solar radiation (Solar) and wind speed (Wind) using monthly relative humidity (MRH) categorical values as the classification variable ($n = 225,270$). Gray dots and attached numbers correspond to MRH categorical values.

2.5. Discretization

The model was built using the software package Netica (Version 6.04, Norsys Software Corp., Vancouver, BC, Canada), which is free for small models with less than 15 variables. For each selected variable, nodes were created and discretized. The discretization of continuous variables in BN leads to the loss of information [11]. An accepted strategy to deal with this is to mimic the data distribution of the variables in the discretization [47,48]; however, the definition of the breakpoints for each state is a major challenge [47,49,50]. There are automatic methods to discretize continuous variables, but the selection of one method over another based on their performance is not clear, and using automatic methods may result in a discretization inappropriate for the purpose of the model and the users. For this reason, expert knowledge remains the best option for discretization [14,47,50].

Here, we seek to estimate monthly relative humidity and the relative humidity of the driest month using a single model. The data distribution for precipitation is narrower for RHDM than for MRH (Figure 1 & Table A1) and thus requires shorter breakpoints to gain enough precision to infer the relative humidity under dry conditions. We, therefore, split the states into two: for the lower values that correspond to the data distribution of the cases² of RHDM the breakpoints are shorter, and for the remaining range, the breakpoints are further apart. For the other proxy variables, intervals of equal length were implemented focusing on reproducing the distribution of the data. States were merged if the resulting states had a frequency distribution close to zero. The number of states of each variable was also based on the level of influence of this variable on relative humidity (see Section 3.1.); the less influence, the less states were defined, thus contributing to reducing model complexity without loss of performance (Figure 3).

We used the metric Spherical Payoff³ to evaluate the contribution of a change in range or the number of states on model performance. If a change in the state's range or number of states performed better, the change remained.

2.6. Model Structure and Parameters

Once the node variables were discretized, the graphical model was learned from 80% of the cases of the dataset MRH ($n = 180,530$). The relative humidity node was set as the target variable, and the machine learning algorithm Tree Augmented Naive Bayes (TAN) was used to learn the model structure (Figure 3). TAN is a Bayesian classifier that incorporates dependencies between attributes by building structures between them [22]. The TAN algorithm drew edges from relative humidity to each proxy variable, and added extra edges between proxy variables. Using the same 80% of the MRH dataset, the Bayesian Counting—Learning Algorithm [18] was used to learn the parameters—prior and conditional probabilities—of all variables in the model. The Counting—Learning Algorithm allows the model to move from initial-ignorance mode to parameterized mode by calculating the conditional probabilities and experience (confidence of the conditional probabilities) of the corresponding combination of variables' states [18,23]. Once the parameter values are learned, the model can be compiled and is ready for use.

² A case is the set of values of the proxy variables and relative humidity for a given month and pixel. For example, in the Figure 3B, the case entered in the net has values only for three variables.

³ The Spherical Payoff is a scoring metric used to test the performance of Bayesian network models. The score goes from 0 to 1, where 1 indicates the best performance [51].

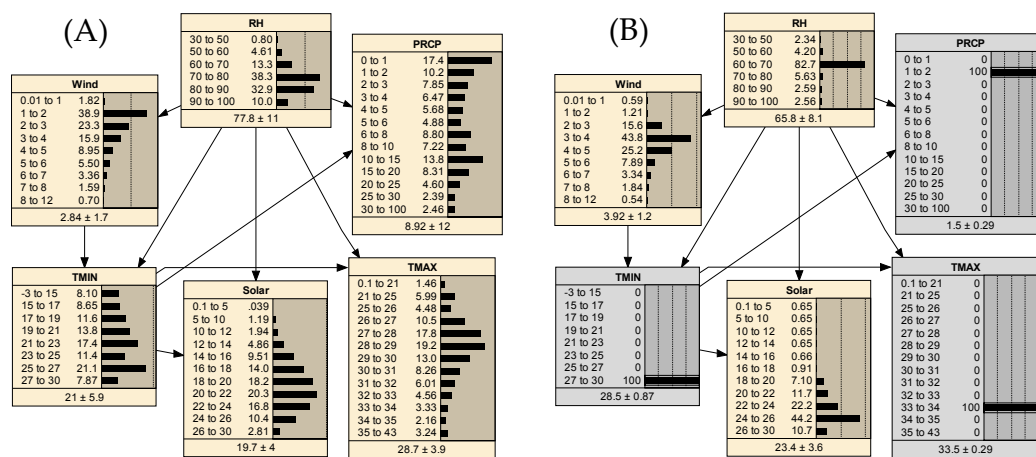


Figure 3. The Bayesian network model to infer monthly relative humidity. (A) Compiled model without evidence entered; (B) Model state when model is inferring the relative humidity of the driest month using only three proxy variables. Grey boxes indicate that evidence (values) were entered for the corresponding variables; the model uses the available new information to update the states of the remaining unknown variables (Wind, Solar, RH). RH: relative humidity (%), TMAX: maximum temperature (°C), TMIN: minimum temperature (°C), PRCP: total precipitation (mm). Graphical structure and parameters learned from the reanalysis dataset CFSR [45,46].

2.7. Sensitivity Analysis and Model Validation

After compiling the model, we did a sensitivity analysis using the variance reduction procedure. The variance reduction estimates the impact of a change in the state of a proxy variable on the state of the target variable [51]. The variance reduction values range from 0 to 100%, where a higher value indicates a higher influence [18,49].

We validated the model in two ways. First, we tested the ability of the model to infer the monthly relative humidity of any given month in the year and the specific relative humidity of the driest month for the same period using all the proxy variables (PRCP, TMAX, Solar, Wind, and TMIN). Second, we explored the capability of the model to infer relative humidity with the variables Solar and Wind missing, which are hardly registered in the study region’s weather stations (Figure 3B). The output value in the second case is the *expected value*, which is the mean of the possible states, weighted by their probability of occurrence [18]. As input data, we used the remaining 20% of the cases of the MRH dataset ($n = 45,190$) for inferring monthly relative humidity, and all the cases of the RHDM dataset ($n = 18,810$) for inferring the relative humidity of the driest month. Then, we compared the inferred to the observed values. For this, we used the metrics RMSE and bias [11,52]. Finally, we provide a spatial comparison between the inferred and reported values described above, and suitability maps of the relative humidity of the driest month for *Coffea arabica* L. for the entire study region.

3. Results and Discussion

Climate variables dynamically interact at the same time and space, and some of these interactions are non-linear relationships. Being able to define our model structure and parameters using learning algorithms was therefore a significant advantage of the Bayesian network approach, which allowed us to capture this natural complexity in a simple explicit graphical model (Figures 2, 3 and A1).

3.1. Sensitivity Analysis

The sensitivity analysis (variance reduction) shows that precipitation and maximum temperature have the highest influence on relative humidity, followed by solar radiation, wind speed and minimum temperature (Table 1). This is expected, as relative humidity is a measure of the water content of air

and variations in precipitation will influence this water content [39,53], and higher temperatures in tropical regions boost evapotranspiration processes, which release water to the air. Despite the low influence of TMIN on relative humidity, the variable has a strong influence on Wind, Solar and TMAX (Table 1), which is a result of the edges added by the TAN algorithm during the structure learning step. The influence between proxy variables is relevant in situations where a variable is unknown. The model can use the known proxy variables to update the states of the remaining unknown proxy variables and the relative humidity (Figure 3B), facilitated by the implicit representation of the joint distribution of the model obtained from the structural and parameter learning [22,23]. The variables PRCP, TMAX and TMIN are thus the most influential in the entire network, and are required by the model to produce enough evidence to obtain good estimates for relative humidity.

Table 1. Results of the sensitivity analysis using variance reduction *. Variables: Relative humidity (RH), precipitation (PRCP), maximum temperature (TMAX), minimum temperature (TMIN), solar radiation (Solar), and wind speed (Wind).

Proxy Variables	Target Variables					
	RH	PRCP	TMAX	Solar	Wind	TMIN
RH	-	25.20	29.30	22.80	18.50	4.68
PRCP	41.80	-	7.70	3.22	0.89	5.42
TMAX	33.90	6.67	-	17.60	7.41	29.60
Solar	17.90	2.36	16.00	-	16.60	21.50
Wind	13.70	2.18	1.73	19.10	-	24.90
TMIN	1.94	3.09	24.20	28.60	45.90	-

* Variance reduction values go from 0 to 100, where a higher score indicates a higher influence on the target variable.

3.2. Validation

The expected values of monthly relative humidity and relative humidity of the driest month were inferred using (1) complete cases for all proxy variables, and (2) incomplete cases, where data of specific variables were missing, in our case once Wind, and once both Solar and Wind. In general, when comparing inferred values to reported values (Table 2), the metrics bias (less than the unit) and RMSE (<5%) indicate a very close agreement between values. As expected, the best model performance was obtained when information on all proxy variables was available; however, even under conditions of missing variables, the results were still very good (Table 2 and Figure 4). The only observable effect of missing variables was a lower model performance when estimated relative humidity values were <60%, which could be the result of the low number of cases in the MRH training dataset in this range (5.3% of total cases; 6 cases at 30–40%, 361 cases <50%, and 2060 cases <60%). Therefore, for some combinations of variable states, there were very few cases defining the conditional relationships (experience) between the variables, and the missing variable conditions increased the uncertainty during the inference.

Table 2. Model performance inferring the monthly relative humidity (MRH) and the relative humidity of the driest month (RHDM) using proxy variables.

Inferred Variable	Cases (Dataset)		Proxy Variables **		Metrics	
	Model Building *	Validation	Known	Missing	BIAS	RMSE
Monthly relative humidity	180,530 (MRH)	45,190 (MRH)	PRCP, TMAX, Solar, Wind, TMIN	-	-0.99	4.03
			PRCP, TMAX, Solar, TMIN	Wind	-0.52	4.13
			PRCP, TMAX, TMIN	Solar, Wind	-0.40	4.13
Relative humidity of the driest month	180,530 (MRH)	18,810 (RHDM)	PRCP, TMAX, Solar, Wind, TMIN	-	-0.26	2.25
			PRCP, TMAX, Solar, TMIN	Wind	-0.76	4.93
			PRCP, TMAX, TMIN	Solar, Wind	-0.08	5.00

* Graphical structure and parameters. ** Proxy variables: Precipitation (PRCP), maximum temperature (TMAX), minimum temperature (TMIN), solar radiation (Solar), and wind speed (Wind).

Eskelson et al. reported similar RMSE values (3 to 4%) in a study in which they used air temperature in a set of linear models to estimate relative humidity in a Riparian forest [44], and Eccel reported RMSE values of 8–11% in his attempt to estimate relative humidity based on temperature and precipitation in the Italian Alps [54]. When comparing the performance metrics to the error of observation inherent in measurements using hygrometers, this study's accuracy falls in the middle of the accepted error range (1 to 5%) set for sensors [39,44]. Even though our metrics are thus similar to the ones reported by other authors, our approach has the additional advantage that it is possible to use new available information on proxy variables to update the states of the unknown proxy variables and therefore the target variable relative humidity (Table 2 and Figure 4). This feature is relevant to real world situations, where missing information is a frequent condition. In the case presented in Figure 3B, the new evidence of PRCP, TMAX and TMIN provoked the update of the states of the (unknown) variables Solar, Wind and relative humidity (see Figure 3: compare the probability distribution of variables in Figure 3A,B).

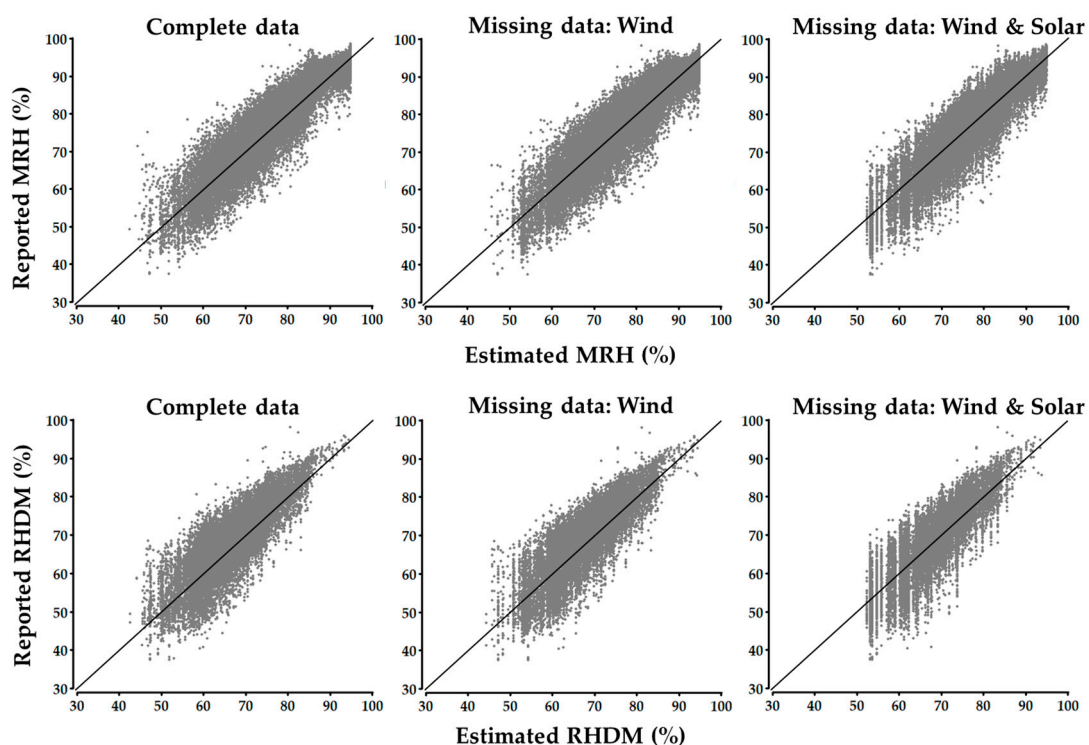


Figure 4. Scatter plot of model-estimated vs. reported values of monthly relative humidity (MRH) and relative humidity of the driest month (RHDM) using complete and incomplete data. Wind: wind speed, and Solar: solar radiation. Data source: reanalysis dataset CFSR [45,46].

Finally, we present a spatial comparison of model-estimated vs. reanalysis-reported RHDM values, and a suitability map of RHDM for coffee production over the region of Central America and Southern Mexico (Figure 5). It shows that the model reproduces the general spatial patterns well and coffee areas are located mainly in areas with high to medium RHDM-suitability. Thus, the relative humidity estimated with the method described in this study can be used reliably in spatially explicit land evaluation tools such as the model ALECA (Agroecological Land Evaluation for *Coffea arabica* L.), which consists of several climate, soil and landform variables that together describe and evaluate the suitability of land units for the production of Arabica coffees [55].

Other potential areas of application for this method are in paleoclimatology, where missing information is a normal situation, in meteorology and climate science to predict and explore the dynamics between climate variables, or in crop modeling applications, where available datasets are

frequently incomplete. In the future, we plan to include the use of Dynamic Bayesian Networks to estimate a variable's values at different time steps considering the previous state values and new information [56,57].

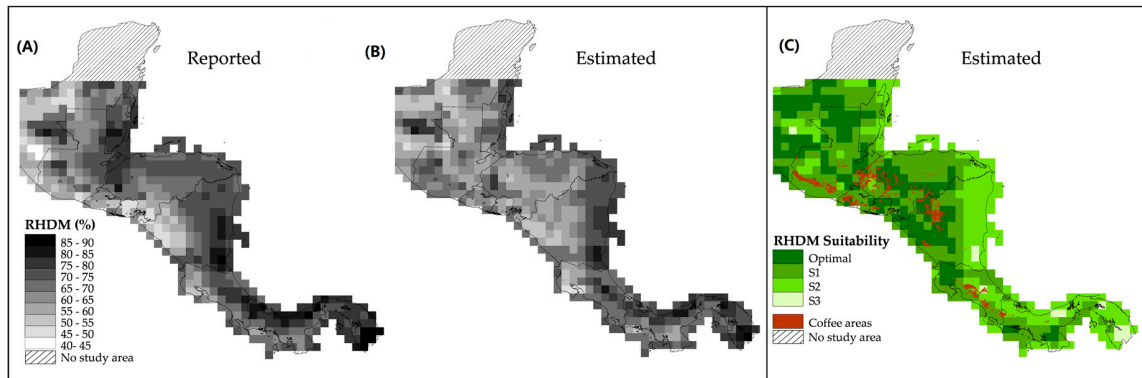


Figure 5. Maps of relative humidity of the driest month (A) reported in the CFSR reanalysis dataset for Central America and Southern of Mexico (pixel size 38 km × 38 km); and (B) estimated with our BN model. (C) Suitability map of relative humidity of the driest month for *Coffea arabica* L. based on the estimated values using complete dataset. Reference year: 2000. Suitability map (modified from [24]): Optimal = Optimal conditions (50–60%), S1 = Very good (40–50% & 60–70%), S2 = Moderate (7–80%), S3 = Marginal (>80%).

3.3. Caveats

We used a complete dataset to create the model (structure and parameters); however, incomplete data is a common situation in the study area. Bayesian networks can deal with this situation by using learning algorithms for missing data, such as the Expectation-Maximization or Gradient Descent algorithms. Their implementation (in Netica) is similar to the steps described here using the Counting-Learning Algorithm [18,58,59].

It should also be kept in mind that if the model is used in a different region, or with data of a higher resolution, variable states such as the range and maximum and minimum values need to be adjusted to the new conditions. In addition, in a high-resolution analysis, the addition of topographic and location (latitude and longitude) variables to the model may become necessary, as altitude, for example, can influence relative humidity at a local scale [60,61] and location could capture the spatial variability of the climate variables in the region. Further adjustments would also be necessary if the time step is changed from monthly to weekly or daily. Lastly, even though we built the model to estimate relative humidity, this method is equally suited for inferring missing values for other climate variables.

4. Conclusions

In this paper, we describe the application of a Bayesian network to generate missing data of relative humidity based on its relationship to proxy variables. The procedure is simple, requires a low modeling effort, and ensures that the relationships between all climatic variables remain consistent throughout the process. The model shows a good performance estimating relative humidity, even in cases of uncertainty when proxy variables are missing. We conclude that Bayesian networks are a suitable tool for estimating relative humidity for agricultural planning, an essential and less-explored domain for the application of probabilistic graphical models.

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Author Contributions: Leonel Lara conceived, designed, developed, and performed the modeling and wrote the paper. Livia Rasche, Uwe Schneider, and L. Enrique Sucar supported the modeling performance analysis and the writing processes. Livia Rasche edited the paper. Uwe Schneider contributed with materials and analysis tools.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary statistics of relative humidity (RH), precipitation (PRCP), maximum temperature (TMAX), solar radiation (Solar), wind speed (Wind) and minimum temperature (TMIN) from the datasets MRH and RHDM. MRH: monthly relative humidity, and RHDM: relative humidity of the driest month. Data source: surface reanalysis dataset Climate Forecast System Reanalysis (CFSR) [45,46].

Dataset	Variable	Unit	Mean	S.D.	Median	Minimum	Maximum	Skewness	Kurtosis
RHDM	RH	%	69.13	9.08	70.16	37.45	98.16	−0.41	−0.18
	PRCP	mm	1.05	1.79	0.47	0.00	24.41	4.19	24.69
	TMAX	°C	29.76	3.33	29.27	10.00	42.35	0.24	0.94
	Solar	MJ/m ²	21.53	3.10	21.74	7.93	28.27	−0.39	−0.17
	Wind	m/s	3.37	1.73	2.85	0.77	11.51	1.08	0.64
	TMIN	°C	20.53	4.93	20.92	−2.66	29.17	−0.57	−0.26
MRH	RH	%	77.79	9.66	78.50	37.45	98.73	50.04	0.37
	PRCP	mm	8.13	8.38	5.47	0.00	83.94	−146.41	4.01
	TMAX	°C	28.75	3.05	28.48	10.00	42.35	−5.03	1.71
	Solar	MJ/m ²	19.69	3.83	20.03	3.72	28.27	39.49	−0.04
	Wind	m/s	2.83	1.58	2.32	0.63	11.81	−109.93	1.35
	TMIN	°C	21.51	4.40	21.85	−2.66	29.54	50.07	−0.13

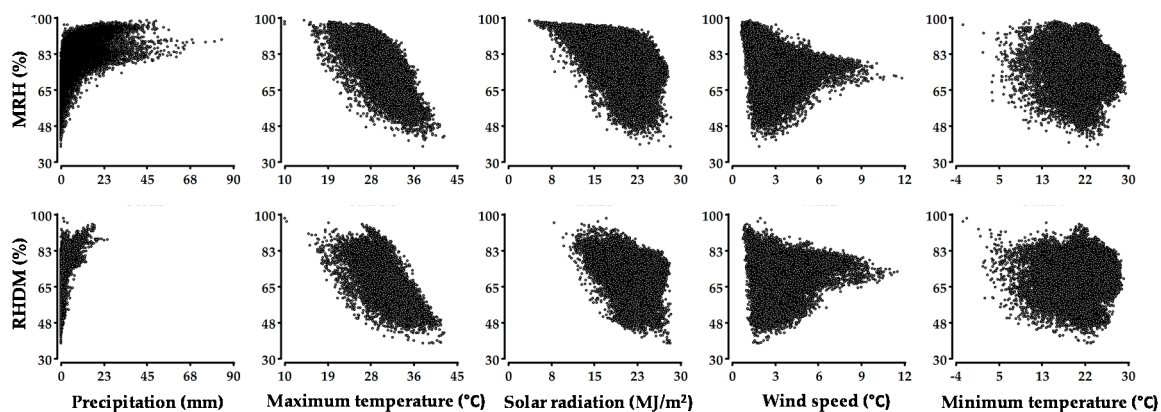


Figure A1. Scatter plots of variables monthly relative humidity (MRH), and relative humidity of the driest month (RHDM). Data source: surface reanalysis dataset Climate Forecast System Reanalysis (CFSR) [45,46].

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