Application of GSTAR kriging model in forecasting and mapping coffee berry borer attack in Probolinggo district

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Abstract. Generalized Space Time Autoregressive (GSTAR) is one of multivariate time series modeling that considers aspects of location with heterogeneous location characteristics. The GSTAR model normally can only be used in forecasting an event in the future at the observed locations. The problem that often occurs in some cases is that there are locations to be modeled that do not have sufficient or incomplete data as data in other locations. For this reason, several alternatives can be done, and one of them is by combining the GSTAR model with the kriging interpolation technique. This modeling is known as GSTAR Kriging modeling. In this research, GSTAR Kriging modeling is applied in predicting and mapping coffee berry borer attacks in Probolinggo District. The model parameters are estimated using the GLS method in the SUR equation system. Forecasting results indicate that the GSTAR Kriging model has a high forecasting accuracy and is not much different from the GSTAR model. Meanwhile, based on the forecasting map, it can be seen that the peak of coffee berry borer attack is predicted to occur in July 2019 with the attack center located in Tiris Sub-district.

1. Introduction

The Generalized Space Time Autoregressive Model (GSTAR) is a type of modeling used in forecasting multivariate time series data that involves aspects of location. The GSTAR model is more appropriate for heterogeneous locations. Estimation of GSTAR model parameters using OLS has weaknesses, namely the results of parameter estimation are inefficient when the inter-location residuals are correlated. Therefore, Iriany, et al. introduced the Seemingly Unrelated Regression (SUR) approach by using Generalized Least Square (GLS) as a method of estimating model parameters (1)[1]. The SUR approach proves to be able to provide more efficient parameter estimation results than OLS. GSTAR modeling with the SUR approach is known as GSTAR-SUR modeling.

The GSTAR model normally can only be used in predicting an event in the future in locations where the data is indeed used in forming the model. The problem that sometimes occurs in some cases is that not all locations that want to be modeled do not have data, or if there is data, the data is not as complete as other locations. To that end, several alternatives can be done, one of which is to combine the GSTAR model with interpolation techniques. Research on this subject has only been conducted by Abdullah, et

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al. (2018), which combines GSTAR with kriging interpolation technique known as GSTAR-Kriging modeling. In that study, parameter estimation was performed using the OLS method.

In this research, we propose the GSTAR Kriging model using the SUR approach in estimating model parameters. The case study used in this study was forecasting coffee berry borer attack in Probolinggo District. This case study was chosen with the consideration that coffee is a commodity that has an important role for the national economy and has a high economic value. One of the problems in the coffee industry is the low productivity of coffee plants and the low quality of coffee beans. One of the factors causing this is the high attack of pests and diseases. One of the main pests that attack coffee plants is coffee berry borer, where the damage of coffee beans by this pest can reach 40-50 percent of the weight of coffee beans. One of the centers of coffee berry borer infestation in East Java Province is Probolinggo District. This research aims to determine the order of the GSTAR model and test whether the GSTAR-SUR Kriging model can be used in predicting coffee berry borer attacks with forecast accuracy as well as the ordinary GSTAR-SUR model.

2. Literature review
2.1. GSTAR model

GSTAR model with autoregressive order \( p \) and spatial order \( \lambda \) can be written [3]:

\[
Z(t) = \sum_{k=1}^{p} \sum_{l=0}^{\lambda_k} \phi_{kl} W^{(l)} Z_{(t-k)} + \varepsilon(t)
\]

where,

- \( Z(t) \) : \((N\times1)\) vector observations at the \( t \)-time
- \( \lambda_k \) : spatial order from \( k \)-th AR
- \( \phi_{kl} \) : diagonal matrix with diagonal elements as AR and space-time for each location \( (\phi_{kl}^{(1)}, \ldots, \phi_{kl}^{(N)}) \)
- \( \varepsilon(t) \) : white noise with an average vector of 0 and a matrix of variance-covariance \( \sigma^2 I \).

2.2. Estimation of models parameter using seemingly unrelated regression (SUR)

Seemingly Unrelated Regression (SUR) model is used for multivariate regression analysis when the residual variables correlate between equations [4]. SUR model consists of several equations in which the remainder does not correlate between observations in one equation, but correlates between one equation with another. SUR model with \( m \) equations is stated as follows [5]:

\[
Z = X\beta + \varepsilon
\]

Assumptions that must be met in the SUR model are \( E(\varepsilon) = 0 \) and \( E(\varepsilon\varepsilon') = \sigma_i I_T \) where \( i, j = 1,2,\ldots, m \). Variance-covariance matrix stated by \( \Omega \) as follows:

\[
\Omega = \Sigma \otimes I_T
\]

where matrix \( \Omega \) sized \((N\times T) \times (N\times T)\).

Parameter estimation in GSTARX-SUR model is done by applying the Generalized Least Square (GLS) method, namely by minimizing the number of general squares \( \varepsilon' \Omega^{-1} \varepsilon \) [6]. The results from GLS estimators for GSTAR-SUR and GSTARX-SUR models are obtained with the following formula:

\[
\hat{\beta} = (X'\Omega^{-1}X)^{-1}X'\Omega^{-1}Z
\]

2.3. Kriging interpolation

Kriging interpolation is a mathematical function for estimating values at locations where data is not available or not sampled based on the sampled points around it using the semivariogram model. Semivariogram is one function that describes and models the spatial autocorrelation between data from a variable and functions as a measure of variance [7]. Semivariogram is divided into two kinds, namely experimental semivariogram and theoretical semivariogram. An experimental semivariogram is based on the value of spatial correlation between two variables separated by a certain distance. The experimental semivariogram is formulated as follows [8]:
\[ y^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(s_i + h) - Z(s_i)]^2 \]  

(5)

where,

- \( s_i \): sample point location
- \( Z(s_i) \): observation value at location \( s_i \)
- \( h \): the distance between two sample points
- \( s_i, s_i + h \): pair of sample points within \( h \)
- \( N(h) \): the number of data pairs that have a distance \( h \)

After the experimental semivariogram values are obtained, parameters can be calculated to be used for theoretical semivariogram calculations. Some parameters used to find values in theoretical semivariograms are sill, nugget, and range [9]. After obtaining the values of the three parameters, the theoretical semivariogram values are calculated, and then compared with the experimental semivariogram. There are various experimental semivariogram models, including: spherical, exponential, gaussian, circular and linear models.

2.4. The coffee berry borer

The coffee berry borer is a major pest in coffee plantations worldwide [10]. The coffee berry borer is a dark black beetle borer, known as *Hypothenemus hampei* Ferr. The coffee berry borer is a major plant pests of coffee plants because of its rapid development [11]. The coffee berry borer attacks on young fruits cause fruit declines, whereas attacks on fairly old fruit cause defective holes and poor quality coffee beans [12;13]. This means that coffee berry borer attacks not only cause low production but also reduce the quality of coffee beans, which results in increased costs for sorting defective seeds. Population dynamics and patterns of infestation by the coffee berry borer are closely related to climate factors such as rainfall and relative humidity, and the physiology of coffee plants [13].

3. Data and methods

The data used in this study is the percentage of coffee berry borer infestation and monthly rainfall in 10 villages in the largest coffee producing district in the Probolinggo District, East Java Province. The data is divided into two, namely training data (January 2014 - June 2019) and testing data (July 2019 - September 2019).

The stages of GSTAR-SUR modeling in this study include: (1) Testing the stationarity of data; (2) Model order identification; (3) Estimation and significance test of the parameters of the GSTAR model; (4) Diagnostic examination of the GSTAR model; (5) Forecasting using the GSTAR model; (6) Estimated parameters of the GSTAR Kriging model; (7) Forecasting using the GSTAR Kriging model, (8) Test the reliability of the GSTAR Kriging forecast model and (9) Mapping the results of the GSTAR Kriging forecast model.

4. Results and discussion

4.1. Data stationarity testing

The assumption of data stationarity is very important in forecasting models because the model producing accurate forecasting comes from stationary data on mean and variance. Based on the data plot, it was known that the variance was still not constant, so Box-Cox transformation was needed. After the data is transformed and the variance has been constant (stationary), then test of stationarity on mean was performed using the Dickey Fuller test. The test results show that the data has been stationary on mean, so differencing can be ignored.

4.2. Identifying the order of GSTAR models

The spatial order in this study was limited to \( \lambda = 1 \), while the order of time (\( p \)) was determined through the MPCCF and AICC schemes. Based on the MPCCF and AICC schemes it can be concluded that the order \( p = 1 \). Taking into account the data plots showing that coffee berry borer attacks data tend to have
a 12-month seasonal pattern, in addition to lag 1, in the GSTAR model time order also added lag 12, so that the GSTAR model \((\lambda, p)\) with spatial lag 1 expressed as GSTAR \((1, [1, 12])\).

4.3. Estimation of GSTAR model parameters

Estimation of GSTAR model parameters was done by using the OLS method first to generate the remainder. Furthermore, from the remainder obtained from the OLS method, a matrix of variance covariance obtained will be used in estimating model parameters using the SUR method. In summary, the estimation results of the GSTAR-SUR model parameters are presented in Table 1.

**Table 1.** The estimated results of the GSTAR-SUR model parameters.

| Location | \(\phi_{10}^{(1)}\) | \(\phi_{120}^{(1)}\) | \(\phi_{11}^{(1)}\) | \(\phi_{12}^{(1)}\) | \(\beta\) | \(\beta\) | \(p\)-value | Sig. |
|----------|--------------------|--------------------|-------------------|----------------|---------|---------|-------------|-----|
| Z_1      | 0.452              | 0.269              | 0.156             | 0.120          | 0.000   | 0.032   | NS          | *** |
| Z_2      | 0.282              | 0.072              | 0.348             | 0.298          | 0.084   | 0.616   | NS          | **  |
| Z_3      | 0.434              | 0.007              | 0.191             | 0.370          | 0.002   | 0.185   | NS          | *** |
| Z_4      | 0.167              | 0.173              | 0.491             | 0.135          | 0.221   | 0.299   | NS          | **  |
| Z_5      | 0.274              | 0.116              | 0.384             | 0.429          | 0.057   | 0.517   | NS          | **  |

**NS** : Not Significant  
*** : Significant at \(\alpha=1\%\)  
** : Significant at \(\alpha=5\%\)  
*  : Significant at \(\alpha=10\%\)

There are 4 parameters of the GSTAR-SUR model \((1, 1 [12])\) which are assumed at each location. The first is \(\phi_{10}^{(i)}\), if the estimated value of this parameter is significant, this indicates that the attack at the \(i^{th}\) location was affected by the attack on the previous month at the same location. Second, \(\phi_{120}^{(i)}\), shows that if this parameter is significant, this means that the attack at the \(i^{th}\) location was affected by the attack 12 months earlier at the same location. The third parameter, \(\phi_{11}^{(i)}\), if significant, this indicates that the attack at the \(i^{th}\) location was affected by the attack in the previous period at another location located around the \(i^{th}\) location. The last parameter, \(\phi_{12}^{(i)}\), if significant, then this indicates that the attack at the \(i^{th}\) location was affected by the attack 12 months earlier at another location located around the \(i^{th}\) location.

From the estimation results of the GSTAR model parameters in Table 1, it can be seen that there were locations where the coffee berry borer attack was affected by the attack one month earlier at that location, some were affected by the attack one month and one year earlier at that location, and some...
were affected by the one attack the previous month that occurred at the surrounding location. This shows that the coffee berry borer attack in Probolinggo District was influenced not only by the time aspect, but also by the spatial aspect.

4.4. Diagnostic examination GSTAR model
White noise assumption testing is used to determine whether there is a correlation between residuals generated from the GSTAR-SUR model. Testing white noise assumptions using MCCF. Test criteria if there is no real lag in the MCCF scheme, the residuals were white noise, whereas if there is a real lag in the MCCF scheme, the residuals are not white noise. Based on the MCCF scheme it is known that lag 1 and 2 on the MCCF scheme were not statistically significant. This means that the residual in the GSTAR-SUR model was declared white noise.

4.5. Forecasting using GSTAR model
By using the GSTAR and GSTARX models that are formed, the coffee berry borer attack forecasting can be done. Figure 1 below presents a plot of prediction data (forecast) and actual data in Segaran Village, Tiris Subdistrict.

![Figure 1. Actual and prediction (forecast) data plots using GSTAR models in Segaran village, Tiris subdistrict.](image)

Based on Figure 1, it can be seen that the predicted value approaches the actual value. It's just that, in certain months where attacks have peaked, forecast results were generally lower than the actual value. This shows that the GSTAR model obtained still has a weakness, that was less able to overcome the overdispersion that occurs in the data. The surge in attacks that began in 2016 was less able to be captured properly even though the attack patterns are still able to be followed by the model. Some alternatives that might be done in the future are by adding exogenous variables to the model to improve the accuracy of the model. In addition to forecasting accuracy, with the exogenous variables, forecasting will be more informative and useful. GSTAR modeling by entering this exogenous variable is known as the GSTAX model. This exogenous variable can be in the form of metric and non-metric.

4.6. Estimation of GSTAR kriging model parameters

4.6.1 Estimation of GSTAR model parameters at the observed location. In this study, it will be simulated that from 10 villages in Probolinggo district, there are 9 villages whose data are completely available and 1 village whose data is not available, i.e.: Watupanjang village, Krucil subdistrict. This village was chosen as an unobserved location because the location of coffee plantations in the area is
difficult to reach. Modeling GSTAR-SUR in 9 locations was observed carried out in stages as modeling GSTAR-SUR in 10 locations. The forecasting stage is carried out after the kriging interpolation process to get the estimated value of the GSTAR-SUR Krigeing model parameters in an unobserved location.

4.6.2 Estimation of GSTAR model parameters at the unobserved location. Estimation of model parameters at unobserved locations is done by kriging interpolation, i.e., using the estimated values of model parameters at 9 observed locations. The first stage in kriging interpolation is to determine the empirical semivariogram to be compared to the terroritic semivariogram. Then the theoretical semivariogram is selected that best suits the empirical semivariogram. The selection of theoretical semivariogram models is determined by looking at the smallest AIC value. Then estimating the parameters of the semivariogram model is then used to interpolate in unobserved locations. A summary of the results of the estimation of selected semivariogram model parameters for each GSTAR model parameter can be seen in Table 2.

Table 2. Estimation results of selected semivariogram model parameters for each GSTAR-SUR model parameter.

| GSTAR Model Parameters | Semivariogram Parameter Estimate | Nugget | Sill | Range |
|------------------------|----------------------------------|--------|------|-------|
| φ_{10}                 | Exponential                      | 0.0410 | 1.00E-06 | 1.3923 |
| φ_{120}                | Exponential                      | 0.0310 | 1.00E-06 | 1.8790 |
| φ_{11}                 | Exponential                      | 0.0310 | 1.00E-06 | 1.8790 |
| φ_{121}                | Exponential                      | 0.0613 | 1.00E-06 | 1.8153 |

Furthermore, based on the selected semivariogram model, interpolation can be done using the ordinary kriging method to get the estimated value for each GSTAR model parameter at an unobserved location, namely Watupanjang village. Comparison of the results of estimating the parameters of the GSTAR Kriging model with the ordinary GSTAR model in Watupanjang is presented in Table 3.

Table 3. Comparison between estimation result of GSTAR and GSTAR kriging model parameters in Watupanjang village.

| Parameter (β) | Estimate (β̂) | GSTAR Kriging | GSTAR |
|---------------|---------------|---------------|-------|
| φ_{10}^{(1)}  | 0.617         | 0.602         |
| φ_{120}^{(1)} | 0.228         | 0.224         |
| φ_{11}^{(1)}  | 0.053         | 0.086         |
| φ_{121}^{(1)} | 0.084         | 0.068         |

From Table 3 it can be seen that the estimated value of the four parameters of the GSTAR Kriging model does not differ greatly from the estimated values of the four parameters of the GSTAR model. This shows that parameter estimation using interpolation technique at unobserved locations in GSTAR Kriging modeling is quite good. The estimation results of the model parameters in both the observed locations and one unobserved location are then used to form the GSTAR Kriging models to predict the coffee berry borer attacks in 10 locations.

4.7. Forecasting using GSTAR kriging models

Based on the forecasting model, forecasting is then performed using the one step ahead method for the next three months. Figure 2 below presents a plot between actual data and forecast results using the GSTAR Kriging model at an unobserved location, Watupanjang village.
Figure 2. Actual and forecast data plots using GSTAR kriging model at an unobserved location.

From Figure 2 above, it can be seen that the forecast value for July and September approaches the actual value, but this is not the case for August, where the forecast is somewhat different from the actual value. This might have happened because in August there were still a lot of coffee fruits that had not been harvested, but it could also be due to other factors such as climate change where in 2019 it was estimated that there was a long dry season starting in April - May for Probolinggo District. So in 2019 there is a shift in the peak attack of coffee berry borer which usually occur in June or July, for 2019 the peak of attacks occur in August. This is less able to be captured properly by the model.

4.8. Test of reliability of GSTAR-SUR kriging forecasting models

To determine the reliability of the GSTAR-SUR kriging model as a whole, the comparison accuracy forecasting test was conducted between the GSTAR-SUR kriging model and the ordinary GSTAR-SUR model by using several measures of model goodness, i.e.: RMSE and MAPE calculated from forecasting data compared to forecasting data actual data (out-sample data). Forecasting models are said to be reliable if they have a MAPE value of less than 10%. Table 4 presents a comparison of RMSE and MAPE values between the GSTAR-SUR model and the GSTAR-SUR kriging model at each location.

| Location | Z1 | Z2 | Z3 | Z4 | Z5 | Z6 | Z7 | Z8 | Z9 | Z10 | Avg  |
|----------|----|----|----|----|----|----|----|----|----|-----|------|
| RMSE     |    |    |    |    |    |    |    |    |    |     | 0.03 |
| GSTAR-SUR| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0  | 0.03 |
| GSTAR-SUR Kriging | 3  | 5  | 4  | 3  | 3  | 4  | 4  | 4  | 3  | 2    | 0.04 |

| MAPE (%) |    |    |    |    |    |    |    |    |    |     | 0.04 |
|----------|----|----|----|----|----|----|----|----|----|-----|------|
| GSTAR-SUR | 4.8 | 8.9 | 6.9 | 3.7 | 3.7 | 4.9 | 4.7 | 5.2 | 4.6 | 2.5  | 5.04 |
| GSTAR-SUR Kriging | 7  | 3  | 0  | 8  | 7  | 6  | 2  | 3  | 8  | 5    | 5.11 |

From Table 4, it can be seen that the RMSE and MAPE values of the GSTAR-SUR Kriging model are not much different from the RMSE and MAPE values of the ordinary GSTAR-SUR model. The MAPE value of both models is quite low, i.e. less than 10%, indicating that both models, GSTAR-SUR and GSTAR-SUR Kriging have good forecasting accuracy. In other words, the forecasting accuracy of the GSTAR-SUR Kriging model is not lower than the usual GSTAR-SUR model. Thus it can be said that the GSTAR-SUR Kriging model is GSTAR Kriging models are reliable for use in predicting coffee berry borer attacks when there is one location that does not have complete data.
When compared with the OLS approach as used in previous studies, the accuracy of the forecast GSTAR-SUR Kriging model is higher than the GSTAR-OLS Kriging model. This is indicated by the MAPE values of both models. Overall MAPE value using the GSTAR-SUR model of 5.11%, smaller than the overall MAPE value using the GSTAR-OLS model which reached 6.18%. This shows that the SUR approach is more appropriate than the OLS method for estimating GSTAR model parameters.

4.9. Mapping of forecasting results of GSTAR kriging models

The map made is a map of coffee borer attack predictions which is the result of coffee berry borer attack forecast interpolation in 10 locations in 6 coffee-producing districts in the Probolinggo district as a result of the GSTAR-SUR Kriging model. Map of forecasting coffee berry borer attack in July-September 2019 results from GSTAR Kriging modeling are presented in Figure 3-5.

**Figure 3.** Coffee berry borer attack forecast map in Probolinggo district on July 2019 results of GSTAR-SUR kriging modelling.

**Figure 4.** Coffee berry borer attack forecast map in Probolinggo district on August 2019 results of GSTAR-SUR kriging modelling.
Figure 5. Coffee berry borer attack forecast map in Probolinggo district on September 2019 results of GSTAR-SUR kriging modeling

From the forecast map of the coffee berry borer attack as a result of the GSTAR Kriging modeling, it can be seen that the coffee berry borer attack in July 2019 is predicted to be quite high in the eastern region of Probolinggo District, especially in the Tiris District area. The coffee berry borer attacks in the eastern region of Probolinggo are relatively higher than attacks in the western region of Probolinggo considering that the types of coffee grown in the eastern area of Probolinggo are generally robusta coffee types which are indeed more susceptible to this the coffee berry borer attack. The coffee berry borer attack is predicted to begin to decline in August in almost all regions. The coffee berry borer attack in September 2019 is predicted to have decreased and the intensity of the attacks is predicted to be no more than 7%.

Based on the forecast map above, it is recommended to the Probolinggo District Plantation Office together with farmers to carry out integrated pest control (IPM) during June to prevent the high intensity of coffee berry borer attacks which are predicted to occur during July 2019 in the Tiris District, Krucil District and Gading District as the result of the forecast obtained. This also needs to be done given the coffee berry borer pest distribution pattern tends to be seasonal, then the success of pest control this year will affect the coffee berry borer attack during the next year's harvest. One effort that can be done is to clean the remaining attacked coffee fruit (not harvested) and not let it just like that to break the life cycle of this pest. The long dry season that occurred in 2019 also has the potential to slow down the flowering phase so that it is predicted that the harvest period of 2020 will retreat from this year, so that the peak of the attack next year is predicted to be slightly backward. If usually the peak of coffee berry borer attacks occur in June and July, then it is estimated that in 2020 the peak of coffee berry borer attacks in the Probolinggo region will be slightly shifted to July and August 2020.

5. Conclusion
Based on the results that have been achieved in the study, it can be conclude that the GSTAR-SUR Kriging model (1, [1,12]) was a reliable model with a high accuracy to predict coffee berry borer attack when there is one location that does not have complete observational data. In addition, the SUR approach is better than the OLS method in estimating GSTAR Kriging model parameters. From mapping result, it can be shown that coffee berry borer attack in July 2019 is predicted to be quite high in the eastern region of Probolinggo District, especially in the Tiris District area. The coffee berry borer attack is predicted to begin to decline in August in almost all regions. The PBKo attack in September 2019 is predicted to have decreased and the intensity of the attacks is predicted to be no more than 7%. As for suggestions for further research, exogenous variables can be added to the GSTAR-SUR Kriging model to improve forecasting accuracy and make the resulting model more useful and informative.
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