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A NONLINEAR PREDATOR–PREY MODELING APPROACH FOR INVESTIGATING PM2.5–TEMPERATURE INTERACTIONS AND AIR QUALITY DYNAMICS

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ABSTRACT

There is still a significant environmental and public health problem in metropolitan areas, and that is the pollution of the air that is produced by fine particulate matter (PM2.5). For the purpose of analyzing the dynamic interaction between PM2.5 concentration and temperature throughout the winter season, which will take place from November 2024 to January 2025, this research offers a nonlinear predator–prey model which will be used. The model is an adaptation of the traditional Lotka–Volterra framework. It takes into account PM2.5 as the prey and temperature as the predator. Additionally, it incorporates a sigmoid functional response to reflect the threshold-based impact that temperature has on the dispersion of particulate matter. For the purpose of model calibration, nonlinear regression and optimization approaches were used. The data for daily PM2.5 and temperature were acquired from the Pollution Control Department and Weather Underground. In order to determine whether or not the system was stable, eigenvalue analysis and the Routh–Hurwitz criteria were used. The findings indicate that there is a stable equilibrium point and a significant agreement between the values that were seen and those that were expected. For the purposes of air quality forecasting, environmental management, and the creation of pollution-control policies, the framework that has been provided offers a highly reliable and easily interpretable instrument.

Keywords: Pollution, Particulates, Temperature, Dynamics, Forecasting

I. INTRODUCTION

Air pollution continues to be one of the most severe environmental concerns that urban communities all over the globe are facing. Fine particulate matter, which is defined as particulate matter with an aerodynamic diameter of less than 2.5 micrometers (PM2.5), is one of the varieties of air pollutants that presents significant dangers to human health and the preservation of the environment. Because of its very tiny size, particulate matter 2.5 (PM2.5) is able to enter the bloodstream and penetrate deep into the respiratory system. This factor contributes to the development of respiratory illnesses, cardiovascular problems, and early death. PM2.5 concentrations in big cities are continually influenced by a variety of factors, including rapid urbanization, industrial operations, emissions from vehicles, and various seasonal climatic conditions. Therefore, it is vital to have a solid knowledge of the processes that drive the dynamics of PM2.5 in order to design efficient methods for managing air quality and preserving public health.

Within the realm of influencing the behavior and dispersion of contaminants in the atmosphere, temperature is an extremely important factor. Alterations in temperature have an effect on the balance of the atmosphere, the height of the mixing, the circulation of the wind, and the chemical processes that take place inside the atmosphere. Temperatures that are lower may lead to temperature inversion layers that trap pollutants near the ground surface, while temperatures that are higher tend to improve vertical air circulation and the dispersion of pollutants. As a consequence of this, the link between temperature and PM2.5 is intricate and ever-changing, and it changes, depending on the geographical location and the time of year. Finding out more about this relationship may give very helpful information about the processes of pollution production, buildup, and clearance.

Statistical analysis, regression techniques, and machine learning algorithms are the primary methods that are used in the conventional methods of investigating the association between PM2.5

and meteorological factors. It is common for these approaches to fail to capture the underlying dynamic interactions and feedback processes between environmental factors, despite the fact that they have valuable forecasting capabilities. Systems that are found in the environment are inherently nonlinear and entail continuous interactions between a number of different components. In light of this, there is an increasing need for mathematical models that are capable of representing these interactions in a more realistic manner and providing a more in-depth comprehension of the behavior of the system across certain time periods.

A robust framework for understanding dynamic systems that are characterized by reciprocal impact and feedback is provided by the predator-prey model, which was first designed by Lotka and Volterra to explain ecological interactions between species. Within ecological systems, the populations of prey expand when circumstances are good, while the numbers of predators manage the amount of prey by various means, including eating. In environmental systems, when one variable drives the development or decrease of another variable, similar notions might be altered to fit the existing framework. According to the findings of this investigation, the concentration of PM2.5 is considered to be the prey component, while temperature is considered to be the predator that controls the levels of particulate matter. Through the use of a nonlinear dynamic framework, this novel interpretation makes it possible to investigate the relationship between PM2.5 and temperature.

A realistic representation of environmental processes is achieved by the incorporation of logistic growth, sigmoid response functions, and periodic forcing components into the model that has been developed. The threshold effects are captured by the sigmoid response, which indicates that temperature has a substantial impact on PM2.5 concentrations only once pollution levels have beyond a critical point. Seasonal and daily forcing factors are included in order to take into account the recurrent fluctuations in the atmosphere that are brought about by weather patterns, solar radiation, and activities carried out by humans. The capacity of the model to recreate observed variations is improved as a result of these modifications, which also improves its prediction performance.

The city of Bangkok, Thailand, which is a fast growing metropolitan center and typically sees increased PM2.5 concentrations throughout the winter season, is the subject of this research. In this paper, a nonlinear predator-prey model for PM2.5-temperature interactions is developed and validated by making use of actual observational data that was obtained between November 2024 and January 2025. Through the development of an innovative mathematical framework that integrates ecological theory and atmospheric science, the study represents a significant contribution to the field of environmental modeling. The results provide support to the improvement of air quality forecasts, contribute to a better knowledge of the dynamics of pollution, and offer useful information to policymakers who are looking for sustainable ways to combat the issues posed by urban air pollution.

II. REVIEW OF LITERATURE

Akanksha, et al. (2023) we postulated a predator-prey model that was more accurate by merging a number of ecological factors with one another. The flocking propensity of preys, as well as the impacts of Allee and cooperation among predators, were included into their model from the beginning. Through temporal analyses based on the Routh Hurwitz stability criteria and Hopf bifurcations-based bifurcation analyses, they investigated the effects of fluctuations in Allee thresholds, the levels of the intensity of hunting cooperation, and predator attack rates with regard to local and global stability. This was done in order to determine how these factors affected the stability of the system. These factors were quite sensitive and served as predictors in terms of the sort of dynamics that populations attained, whether they were stable or displayed oscillations. The researchers discovered Turing instability conditions and demonstrated how random movement may grow leading to the emergence of spatial patterns. This was accomplished by extending their research into a spatiotemporal domain and including diffusion into their investigation. A vivid picture of how Turing patterns may spontaneously arise was shown by their model simulations. This provided confirmation of the mathematical intuition that spatial heterogeneity could occur in these systems of their own volition.

Addison (2017) learned about the traditional Lotka-Volterra model, which has been a cornerstone in the field of research on the connection between predators and their prey throughout the years. Despite the fact that this deterministic model was successful in describing the cyclical nature of such interactions, Addison emphasized that in order for it to be ecologically realistic, it required a substantial number of extensions. Later modifications included the addition of logistic prey population dynamics, more complicated predator functional responses, varied habitat harvesting dynamics, and temporal delays as a result of prey locating and prey processing. On the other hand, Addison underlined that traditional deterministic approaches had a tendency to disregard random variation in the environment. This was done on the premise that random changes in the environment were not significant in big populations. However, this viewpoint was limited due to the fact that ambient noise had the potential to drastically alter population patterns, especially in cases when the populations were very tiny.

Bairagi, et al. (2007) established (another) mathematical model that included an infected prey population as the prey that was prone to predation that was fostered by various predator functional responses. Additionally, the model investigated how infections affect on predator prey systems. By using rigorous methods, they have shown that solutions of all nonnegative beginning conditions exist, that they are unique, and that they are uniformly bounded. The findings of their analytical and biological studies indicated that in the event that prey were infected with a pathogen that was fatal, none of the three prey-predator-pathogen trios could coexist steadily in conditions of prey, predator, and pathogen. This was due to the fact that each prey and predator response was involved in the underlying functional responses. Through the systematic change of infection rate, predator attack rate, however, they demonstrated a continuum of dynamic behaviors that encompass switching behavior between unstable, oscillatory and extinction courses.

III. METHODOLOGY

PM2.5-temperature interaction model

Predator-prey model

There is a mathematical framework known as the predator-prey model that is used to represent the dynamics of the interaction between two populations, namely predators and prey people. This demonstrates how the population of prey rises when resources are available and decreases when predators are present, while the number of predators increases when there is an abundance of prey and decreases when there is a scarcity of prey. In most cases, this interaction results in fluctuating population levels for both groups, with populations of both predators and prey increasing and decreasing in a pattern that is cyclical from time to time. Using this model, one may get an understanding of natural population management and the equilibrium that exists between species in an ecosystem.

We concentrate on the winter season, which spans from November and December 2024 to January 2025, and we utilize PM2.5 and temperature data that we got from the Pollution Control Department and Weather Underground. The research focused mainly on the region around Airport, which is situated at 13.92 degrees North and 100.6 degrees East. Further evaluation of the model's correctness and stability was carried out by means of the eigenvalues analysis. Additionally, the Routh-Hurwitz criteria was used in order to analyze the system's stability, therefore guaranteeing the resilience of the suggested model.

In the current inquiry, the traditional predator-prey paradigm, which was first developed by Lotka and Volterra, is adapted and modified in order to investigate the dynamic interactions that occur between PM2.5 concentrations and meteorological factors (temperature). In this conceptual framework, particulate matter 2.5 is considered to be the "prey" species, while temperature is considered to be the predatory factor that exerts regulatory impact over particulate matter concentrations within the environment. We used a sigmoid function to describe the influence that temperature has on PM2.5 in our model. our function is a qualitative reflection of the Holling Type III functional response. This technique takes into account the critical-point and saturating character of environmental interactions, which is that temperature does not appreciably lower PM2.5 concentrations until after the concentrations have reached a particular level. In comparison to linear forms, this kind of reaction is more realistic and is in harmony with the dynamics of the environment and the atmosphere. In order to define the PM2.5 and temperature model, we will use the following: Prey equation (PM2.5),

$$\frac{dP}{dt} = \alpha P\left(1-\frac{P}{K}\right) - \beta PT\left(\frac{1}{1+e^{-k(P-P_0)}}\right)$$

$$-\delta PT^2+\xi_1 \sin(\omega_1 t+\phi_1) + \xi_2 \cos(\omega_2 t+\phi_2)$$

Predator equation (Temperature),

$$\frac{dT}{dt} = -\gamma PT + \mu \left(\frac{1}{1+e^{-k\,(P-P_0)}} \right)$$

We set Po=85 for the transitions in thermal effect in the model. Most model parameters (listed in Table 1) were estimated by employing nonlinear regression on the 92-day PM2.5-temperature dataset, whilst all of the remaining parameters were determined through optimization by making use of actual observational data. The handling of any missing values and the normalization of the observations were both part of the data preparation that took place before the model training. It is via these processes that the model is able to accurately recreate both short-term variations and seasonal trends in the data that has been seen.

The technique is intended to provide reliable and reproducible findings, making it appropriate for use in the areas of air quality forecasting and the formulation of environmental policy.

Stability of the model

We carried out a stability analysis in order to test the equilibrium points under a variety of scenarios in order to guarantee the resilience and dependability of the proposed predator-prey model. For the purpose of ensuring that the model acts in a consistent manner and generates meaningful predictions over time, this study is absolutely necessary. In particular, we make use of Eigenvalues and the Routh-Hurwitz Criterion in order to evaluate the stability of the model. This helps to guarantee that the equilibrium points continue to be stable and that the system reacts in a predictable manner to changes in the parameters.

Our attention is focused on the equilibrium point, which is the point at which both PM2.5 and temperature are present at levels that are not zero, which reflects their existence in data collected from the actual world. Through the use of calculations, we are able to determine the point of equilibrium for the system of interest.

$(P^*, T^*) = (120.14, 37.32)$

Jacobian matrix at equilibrium point,

$$J(P^*,T^*) = \begin{bmatrix} -0.0153 & 0.1705 \\ -0.0033 & -0.0106 \end{bmatrix}$$

We get the eigenvalues,

$$\lambda_1 = -0.0129 + 0.0236i$$

$$\lambda_2 = -0.0129 - 0.0236i$$

Table 1. Meaning of parameters in the model

Symbol	Meaning	Values of the Parameters
P	PM2.5 concentration	–
T	Temperature	–
t	Time	–
K	Carrying capacity of PM2.5	172
α	Growth rate of PM2.5	0.015
β	Predation rate	0.00191764
k	The slope of the sigmoid function	0.5
δ	PM dispersion rate	-0.0000447
ξ_1	Seasonal forcing	5.9800
ξ_2	Daily forcing	5.5955
ω_1	Frequency of seasonal	0.0100
ω_2	Frequency of daily	6.2458

ϕ_1	Phase shift	2.1401
ϕ_2	Phase shift	3.7893
γ	Temperature decrease rate by PM2.5	0.0000881
μ	Temperature increase by PM2.5 effect	0.3949

All eigenvalues have negative real parts, the system is stable Routh-Hurwitz criterion test, from the eigenvalues (5) and (6) we get the characteristic equation,

$$s^2+0.259s+0.000723=0$$

Which,

$$a_2=1,a_1=0.259,a_0=0.00072$$

There are no sign changes, which mean the system is stable

IV. RESULTS AND DISCUSSION

According to the findings of this research, a nonlinear predator-prey model was created in order to analyze the relationship between PM2.5 concentrations and temperature throughout the winter season. The system is comprised of two coupled differential equations, with PM2.5 being treated as the "prey" and temperature being modeled as the "predators." This system is a unique framework for simulating the atmospheric quality of metropolitan environments. This comparison offers a dynamic systems view, which not only captures correlation but also causation and regulatory processes. This is in contrast to the typical statistical or machine learning techniques, which simply capture correlation. In order to accurately capture seasonal and diurnal dynamics, key processes such as logistic growth, threshold responses, and periodic external forcing were integrated into the model architecture. The predator-prey framework naturally integrates nonlinear feedback and stability analysis, making it more suitable for modeling complex environmental systems with the ability to capture feedback loops and saturation effects. Previous studies frequently rely on regression analysis to analyze air pollution; however, the predator-prey framework does not rely on regression analysis.

Model calibration and equilibrium analysis were carried out with the use of daily observations over the course of 92 days, beginning in November 2024 and ending in January 2025. Either experimentally obtained or approximated using regression fitting, the parameters of the model were determined, as seen in The stability of the model was verified by the use of eigenvalue analysis and the Routh-Hurwitz criteria, which confirmed the existence of a locally stable equilibrium under the circumstances that were observed.

A comparison was made between the projected values of PM2.5 and temperature and the actual measurements in order to assess the performance of the model itself. This comparison is shown in Figure 1, which shows the difference between the PM2.5 concentrations that were measured and the values that were anticipated by the predator-prey model that was suggested. While Figure 2 illustrates the contrast between the actual temperature that was seen and the temperature that was projected by the model throughout the course of the research, Figure 3 shows both variables combined. Both the root mean square error (RMSE) for temperature and the root mean square error (PM2.5) were found to be 15.7036. Significant agreement can be shown between these numbers, which is particularly noteworthy when considering the inherent unpredictability and nonlinearity of urban air systems.

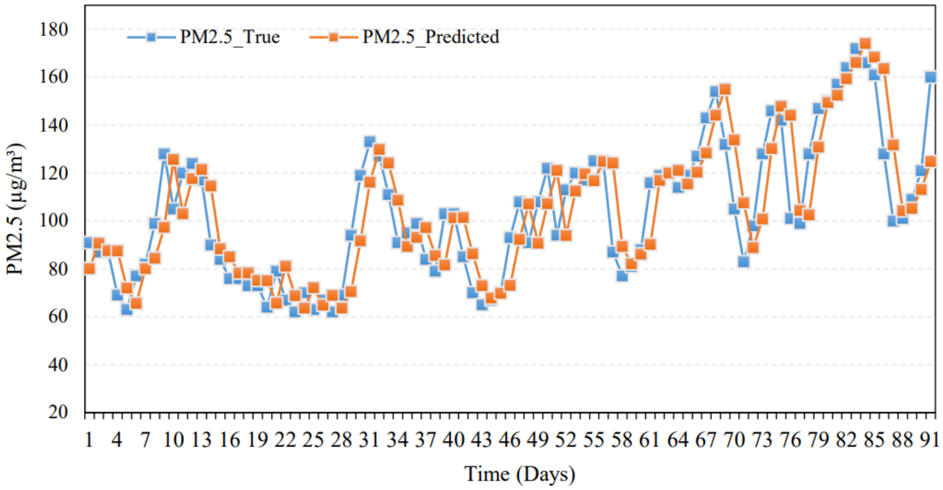

Figure 1. PM2.5 true vs predicted

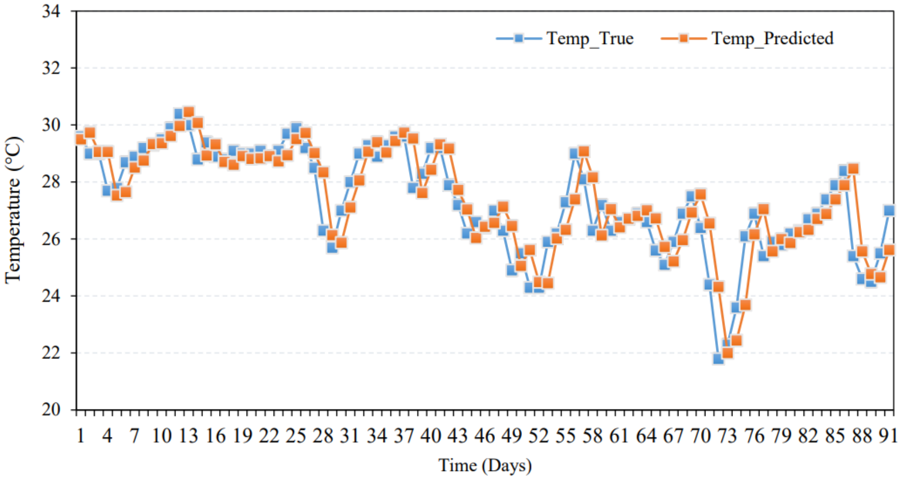

Figure 2. Temperature true vs predicted

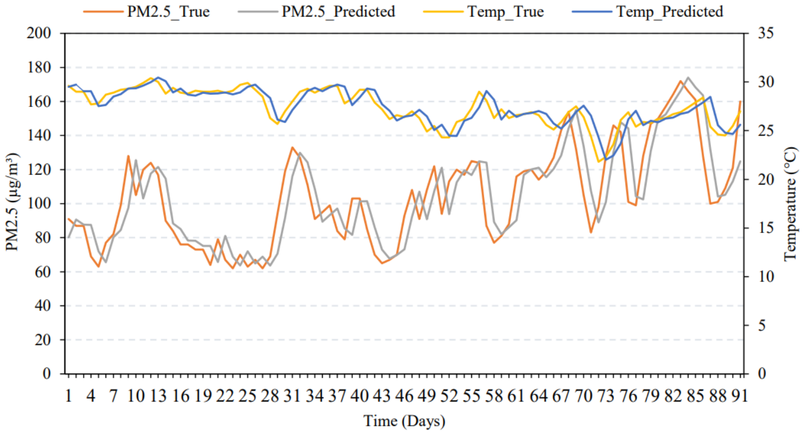

Figure 3. PM2.5 and Temperature true vs predicted

The model not only provides a mechanistic explanation for threshold effects, but it also confirms the known inverse relationship between temperature and PM2.5. Temperature effectively reduces PM2.5 only when pollution levels exceed a critical point, which is consistent with urban temperature inversions. This is the interpretation and implications of the model. This understanding goes beyond the results of empirical research by identifying causal thresholds, which may assist in informing the timing of policy initiatives in a more effective manner. Furthermore, the incorporation of periodic forcing variables, such as daily traffic cycles, contributes to the enhancement of the model's accuracy. This is because it enables the model to capture recurrent PM2.5 peaks that are caused by daily traffic patterns and seasonal fluctuations in solar radiation.

It was decided to use the analogy of a predator and a prey to describe the dynamic connection that exists between temperature and PM2.5. Temperature was shown as the "predator," while PM2.5 was portrayed as the "prey." In urban settings, the dynamics of the boundary layer play a significant part in the regulation of the dispersion of PM2.5, with temperature having an effect on the stability and turbulence of the atmosphere. Additionally, diurnal temperature variation affects the daily cycle of PM2.5 concentrations, as higher day time temperatures enhancing dispersion and lower concentrations, while nighttime inversions trap pollutants near the surface. This mechanical knowledge of physical processes lends validity to the analogy of predators and prey, and it also helps to enhance the ecological foundation upon which the model is built.

By permitting formal study of system stability and prospective regime transitions, the predator-prey method provides higher theoretical depth than typical empirical or data-driven models. This is shown by the fact that it gives better theoretical depth. Examples of this include the discovery of an equilibrium state, which makes it feasible to simulate long-term outcomes under a variety of policy scenarios. This is something that is often not attainable with models that are simply statistical.

In spite of the fact that it only has two variables, the model is able to accurately describe the pollution that occurs in metropolitan areas. Additionally, it provides a versatile basis for future improvements, such as the incorporation of other meteorological factors to improve the accuracy of predictions. Extending the model to include numerous "prey" or "predator" species (for example, various contaminants or atmospheric factors) might significantly increase its usefulness and realism in the work that will be done in the future.

Implications for Your Daily Life: The model that was built provides a useful instrument for daily air quality forecasts, which enables the appropriate authorities to issue public health advisories and pollution alerts that are more accurate. This study focuses on modeling PM2.5 concentrations during the winter season, when pollution levels are typically highest. As a result, the findings and policy recommendations are most applicable to the winter months, and the model’s applicability to other seasons remains limited. By forecasting PM2.5 peaks based on temperature projections, preventive interventions such as traffic management or industrial emission reductions may be adopted in advance to avoid severe pollution events. This can help reduce the severity of pollution incidents significantly. Furthermore, the discovery of a stable equilibrium state offers insights for the development of long-term environmental policy. These insights show that the management of major factors, such as urban heat, might assist in maintaining air quality within acceptable bounds.

This model can be integrated into early warning systems, it can support targeted interventions, such as restricting high-emission vehicles during predicted highpollution periods. Additionally, the conceptual framework of temperature as a regulatory “predator” offers an intuitive way to communicate complex atmospheric dynamics to the public, fostering greater awareness and adherence to health guidelines during critical periods. By integrating this model into early warning systems to support targeted interventions, such as limiting high-emission vehicles during forecasted high-pollution events. Moreover, framing temperature as a regulatory “predator” provides an intuitive and accessible way to communicate complex atmospheric dynamics to both policymakers and the general public, potentially increasing awareness and compliance with health guidelines during critical periods.

While the model demonstrated good accuracy with RMSE values during the three-month validation period, we acknowledge that the short duration limits its robustness. Future work will focus on to expand the validation period by incorporating data from several years of winter seasons, which is when PM2.5 levels are typically the highest. Additionally, out-of-sample validation will be conducted using data from other regions to test the model’s generalizability and long-term applicability across different locations and environmental conditions.

V. CONCLUSION

In order to analyze the dynamic relationship that exists between PM2.5 concentration and temperature in Bangkok during the winter season, this research provides a nonlinear predator-prey model. The model effectively modifies the traditional Lotka-Volterra framework by treating PM2.5 as the prey and temperature as the predator. This provides a fresh viewpoint for comprehending the dynamics of urban air pollutant pollution. The addition of a sigmoid response function, seasonal forcing, and daily forcing into the model makes it possible for the model to reflect the nonlinear and periodic aspects of the environmental data that has been observed. These data provide evidence that the suggested model successfully reproduces the observed patterns of PM2.5 concentration and temperature, demonstrating a high degree of concordance between the values that were predicted and those that were actually observed. The presence of a stable equilibrium point is confirmed by stability analysis conducted with the use of eigenvalue evaluation and the Routh-Hurwitz criteria. This demonstrates that the system continues to be resilient under the circumstances that have been calculated for its parameters. In addition, the findings indicate that temperature has a regulatory effect on PM2.5 concentrations, especially in situations when the levels of pollution above a key threshold. The research demonstrates the value of mathematical modeling in providing an explanation for complicated environmental interactions that goes beyond the scope of typical statistical methods. The suggested framework offers useful insights that may be used for the forecasting of air quality, the monitoring of the environment, and the design of policies. Furthermore, the model provides a basis for future research that will include new atmospheric variables and longer validation periods. This will contribute to the development of more efficient methods for the control of pollution and the management of urban environments in a sustainable manner.

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