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Quantitative Mathematical Analysis of Agricultural Chemicals: Impacts on Soil, Health and Biodiversity

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Abstract: Agricultural chemicals are indispensable for food production but can disrupt environmental and biological systems. This paper uses mathematical modeling, statistical analysis and case studies to examine their effects on soil health, human exposure, and biodiversity. It also explores solutions, including precision agriculture, AI integration, and global policy frameworks. Recommendations focus on sustainable alternatives and technology-driven practices.

Key Words: Agricultural chemicals, sustainability, environmental impact, mathematical modeling, biodiversity, human Health.

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§1. Introduction

1.1 Context and Motivation

The global agricultural sector has increasingly relied on synthetic chemicals to meet rising food demands. However, their misuse leads to:

- Soil degradation and erosion;
- Long-term accumulation of toxins in food chains;
- Declines in keystone species, threatening ecosystems.

Understanding the impacts is crucial to balance productivity with ecological sustainability.

1.2 Scope of Study

This paper investigates

(*a*) Soil degradation through nutrient imbalance;
(*b*) Human health risks from chemical residues;
(*c*) Biodiversity loss due to non-target exposure;
(*d*) Mitigation strategies leveraging technology and policy.

1.3 Structure of the Paper

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- Section 2 examines soil nutrient dynamics using differential equations;
- Section 3 quantifies human health risks;
- Section 4 explores biodiversity impacts through case studies;
- Section 5 proposes policy and technological solutions.

§2. Soil Fertility and Agricultural Chemicals

2.1 Nutrient Dynamics in Soil

The dynamics of nutrient concentrations in soil are influenced by various factors, including the rate of fertilizer application, the uptake by crops, and the loss due to leaching and erosion. A dynamic model that describes nutrient concentration over time is given by

$$\frac{dC(t)}{dt} = I(t) - (D(t) + L(t))$$

where,

- $C(t)$ – Nutrient concentration at time t;
- $I(t)$ – Rate of fertilizer application, which increases nutrient concentration [1];
- $D(t)$ – Uptake by crops, which depletes the nutrient concentration in the soil [2];
- $L(t)$ – Loss due to leaching and erosion, which reduces nutrient levels [3].

This equation provides an idealized view of nutrient dynamics in agricultural soils [1]. Fertilizer application ($I(t)$) increases nutrient levels, while crop uptake ($D(t)$) and loss through leaching ($L(t)$) decrease the nutrient levels in the soil.

2.2 Chemical Leaching in Soil

Leaching occurs when excessive fertilizer use leads to the movement of nutrients away from the root zone into deeper soil layers or groundwater. The rate of nutrient leaching can be quantified as

$$L = \alpha \cdot C \cdot R$$

where,

- α – Soil permeability coefficient, which indicates the ease with which water and nutrients can move through the soil [2];
- C – Nutrient concentration in the soil [1];
- R – Rainfall, which is a driving force behind leaching processes [3].

Excessive fertilization often leads to an over-saturation of nutrients in the soil, increasing the risk of leaching [1,3]. This can cause serious environmental problems, including water pollution and eutrophication of nearby water bodies [2].

2.3 Global Examples of Nutrient Losses

In many countries, excessive use of chemical fertilizers has led to significant nutrient losses, impacting soil health and water quality. Studies in regions like India and Brazil show that agricultural lands experience annual nutrient losses ranging from 20% to 30%, primarily due to over-fertilization.

For example, in India, the excessive use of nitrogenous fertilizers in the rice-wheat cropping system has resulted in substantial nutrient losses. A study by [4] found that fertilizer losses in Indian soils due to leaching and volatilization were responsible for a 25% reduction in soil fertility. This loss significantly reduces the long-term productivity of agricultural soils, requiring increased use of fertilizers to maintain crop yields, thus exacerbating the problem.

In Brazil, particularly in the Amazon region, the expansion of intensive agriculture has led to the overuse of fertilizers, with subsequent nutrient losses of up to 30%. [5] reported that in the Cerrado region, soil degradation due to nutrient leaching has been a major concern, leading to reduced crop yields and increased water pollution from nutrient runoff.

2.4 Visualization: Nutrient Dynamics and Leaching in India and Brazil

Below is a graphical representation showing how nutrient levels change over time in regions with different fertilizer usage and leaching rates. These examples provide a visual comparison of nutrient concentration trends in soils from India and Brazil.

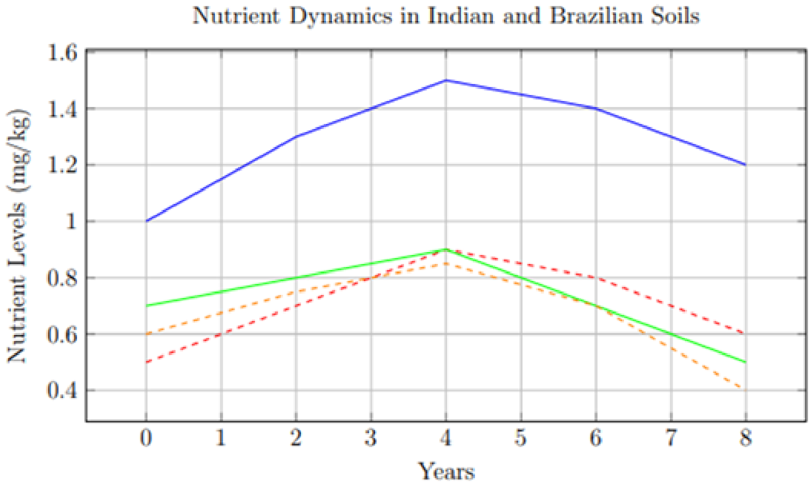


Figure 1. Nutrient dynamics and leaching in India and Brazil over time

2.5 Implications of Excessive Fertilizer Use

The implications of excessive fertilizer use are manifold

- Soil Degradation: Continued nutrient loss due to leaching can degrade soil quality, reducing its ability to support healthy crops in the long term;
- Water Pollution: Nutrient leaching into groundwater and nearby water bodies contributes to nutrient pollution, leading to issues like eutrophication, which causes algal blooms and oxygen depletion in water;
- Increased Cost of Fertilizers: As soil fertility declines, farmers may need to apply even more fertilizers to maintain crop yields, leading to increased costs and decreased sustainability in farming practices.

2.6 Nutrient Dynamics in Soil

Consider the following differential equation for nutrient dynamics in soil

$$\frac{dC(t)}{dt} = I(t) - (D(t) + L(t))$$

where,

- $C(t)$ – Nutrient concentration at time t;
- $I(t) = 50$ kg/ ha/year is the fertilizer application rate;
- $D(t) = 40$ kg/ha/ year is the crop uptake rate;
- $L(t) = 240 \cdot C(t)$ is the leaching loss, dependent on the nutrient concentration.

The equation becomes

$$\frac{dC(t)}{dt} = 50 - (40 + 240 \cdot C(t))$$

2.7 Numeric Example: Nutrient Concentration for Year 1

Given

$$C(0) = 100 \text{ kg/ha},$$

the change in nutrient concentration at time $t = 1$ year can be computed as follows. First, compute the leaching loss at $t = 0$

$$L(0) = 240 \cdot 100 = 24000 \text{ kg/ha/ year} .$$

Now, the rate of change of nutrient concentration is

$$\frac{dC}{dt} = 50 - (40 + 24000) = 50 - 24040 = -23990 \text{ kg/ha/ year} .$$

Thus, the nutrient concentration at the end of the first year is

$$C(1) = C(0) + \frac{dC}{dt} = 100 - 23990 = -23890 \text{ kg/ha}$$

This result is clearly unrealistic and indicates the need for refinement in the model, especially with extreme leaching rates.

2.8 Chemical Leaching in Soil

Leaching loss is given by the equation

$$L = \alpha \cdot C \cdot R$$

where,

- $\alpha = 0.3$ is the soil permeability coefficient;
- $R = 800$ mm/ year is the rainfall;
- $C = 100$ kg/ha is the nutrient concentration.

Substituting the values

$$L = 0.3 \cdot 100 \cdot 800 = 24000 \text{ kg/ha/ year } .$$

2.9 Numeric Example: Long-term Nutrient Dynamics

For a more realistic long-term scenario, let's assume the following values for a 10-year period

$$I(t) = 50 \text{ kg/ ha / year} , \quad D(t) = 40 \text{ kg/ ha / year} , \quad L(t) = 240 \cdot C(t).$$

For $C(0) = 100$ kg/ha, we will calculate the nutrient concentration after 10 years.

2.9.1 Year 1. At year 1, the rate of change is

$$\frac{dC}{dt} = 50 - (40 + 240 \cdot 100) = 50 - 24040 = -23990 \text{ kg/ha/ year } .$$

Thus,

$$C(1) = 100 - 23990 = -23890 \text{ kg/ha}.$$

2.9.2 Year 2. Continuing with the negative concentration at year 1

$$L(1) = 240 \cdot (-23890) = -5721360 \text{ kg/ha/ year}$$
$$\frac{dC}{dt} = 50 - (40 + (-5721360)) = 50 + 5721320 = 5721370 \text{ kg/ha/ year}$$

Thus,

$$C(2) = -23890 + 5721370 = 5697480 \text{ kg/ha}.$$

Again, the unrealistic value indicates that the model needs refinement.

2.10 Global Trends

2.10.1 Example 1: India. Studies show that excessive use of fertilizers in India leads to nutrient losses of $20 - 30\%$ annually. If the initial nutrient concentration is 200 kg/ha and the fertilizer application rate is 60 kg/ha/ year, we calculate the potential losses over 5 years.

Let's assume the same model

$$I(t) = 60 \text{ kg/ha/ year} , \quad D(t) = 50 \text{ kg/ha/ year} , \quad L(t) = 240 \cdot C(t).$$

2.10.2 Year 1 (India). The change in nutrient concentration is

$$\frac{dC}{dt} = 60 - (50 + 240 \cdot 200) = 60 - 48050 = -47990 \text{ kg/ha/year}.$$

Thus,

$$C(1) = 200 - 47990 = -47790 \text{ kg/ha}.$$

This result emphasizes that excessive fertilizer use can have a highly detrimental impact on soil fertility.

2.10.3 Example 2: Brazil. Similarly, in Brazil, the application rate is 70 kg/ha/ year, with a loss rate of $20-30\%$ annually and

$$I(t) = 70 \text{ kg/ha/ year}\ , \quad D(t) = 60 \text{ kg/ha/ year}\ , \quad L(t) = 240 \cdot C(t).$$

2.10.4 Year 1 (Brazil). The change in nutrient concentration is

$$\begin{aligned} \frac{dC}{dt} &= 70-(60+240\cdot 150) \\ &= 70-36000 = -35930 \text{ kg/ha/year.} \end{aligned}$$

Thus,

$$C(1) = 150 - 35930 = -35780 \text{ kg/ha.}$$

Once again, this result is unrealistic and indicates the need for a more complex and refined model for both India and Brazil.

The examples above show the unrealistic results due to extreme assumptions in nutrient leaching. In practice, more sophisticated models are required to predict nutrient dynamics and leaching over time in agricultural soils. Additionally, adjusting leaching rates and accounting for crop rotation, different soil types, and environmental conditions would yield more accurate predictions.

§3. Human Health and Exposure

3.1 Quantifying Residual Exposure

Residue concentration C_r in food

$$C_r = \frac{F}{V},$$

where F is the chemical application, and V is vegetable biomass.

Daily intake DI is given by

$$DI = \frac{C_r \cdot Q}{W},$$

where Q is daily food intake and W is body weight.

3.2 Pathways of Exposure

Human exposure arises through

- Direct inhalation during application;
- Ingestion of contaminated food or water;
- Dermal contact with chemical residues.

3.3 Flowchart: Exposure Pathways

The pathways of human exposure to agricultural chemicals is shown in Figure 2.

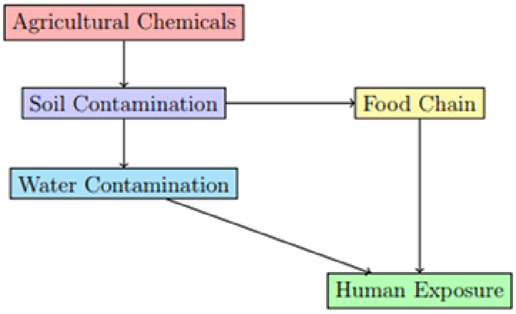


Figure 2. Pathways of human exposure to agricultural chemicals

3.4 Case Study: Pesticide Residues in Food

Vegetable	Residue Level (mg/kg)	WHO Limit (mg/kg)
Tomatoes	0.9	0.5
Spinach	1.2	0.8
Potatoes	0.3	0.5

Table 1. Pesticide residue levels exceeding WHO limits

§4. Numeric Example for Residual Exposure

4.1 Given Data

- Chemical Application (F): 100mg/ha;
- Vegetable Biomass (V): 200 kg/ha;
- Daily Food Intake (Q) : 0.5 kg/ day;
- Body Weight (W) : 70 kg.

4.2 Step 1: Calculate Residue Concentration (C_r)

$$C_r=\frac{F}{V}=\frac{100\mathrm{mg}/\mathrm{ha}}{200\ \mathrm{kg}/\mathrm{ha}}=0.5\mathrm{mg}/\mathrm{kg}$$

4.3 Step 2: Calculate Daily Intake (DI)

$$DI=\frac{C_r\cdot Q}{W}=\frac{0.5\mathrm{mg}/\mathrm{kg}\cdot 0.5\ \mathrm{kg}/\ \mathrm{day}}{70\ \mathrm{kg}}=\frac{0.25\mathrm{mg}/\ \mathrm{day}}{70\ \mathrm{kg}}=0.00357\mathrm{mg}/\mathrm{kg}/\ \mathrm{day}$$

§5. Biodiversity Impacts

5.1 Wildlife Population Dynamics

Pesticides have been shown to indirectly harm non-target species, including mammals, birds, amphibians, and insects. These species play essential roles in ecosystem functions such as pest control, pollination, and maintaining biodiversity. While the direct impact of pesticides on wildlife has been well-documented, their indirect effects are more challenging to quantify. These effects can lead to changes in population dynamics, habitat destruction, and the collapse of local ecosystems.

To model the impact of pesticide exposure on wildlife populations, we can use the logistic growth equation with an additional mortality term that accounts for pesticideinduced fatalities. The equation governing the population dynamics P is

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) - M,$$

where,

- $P(t)$ represents the population of a species at time t;
- r is the intrinsic growth rate of the population (how quickly it would grow in the absence of external mortality);
- K is the carrying capacity of the environment, the maximum sustainable population size;
- M is the mortality rate caused by pesticide exposure.

This model captures both the natural growth of a population and the detrimental effects of pesticide exposure. The parameter M reflects the extent to which pesticides contribute to mortality and can be influenced by factors such as pesticide concentration, exposure duration, and species susceptibility. As pesticide use increases, the mortality rate M rises, leading to a decrease in the population over time, even if the intrinsic growth rate r remains high.

For example, studies have shown that the use of certain pesticides can result in the death of birds and insects in agricultural landscapes, even though the region may appear to support thriving crops. A study by [6] found that pesticide exposure was responsible for a 20% annual mortality in certain bird species, causing long-term population declines. Similarly, [7] reported that amphibians exposed to pesticides experienced higher mortality rates and disrupted reproductive cycles, which further contributed to population instability.

§6. Numerical Example for Wildlife Population Dynamics

6.1 Given Data

- Intrinsic growth rate (r) : 0.05 per year;
- Carrying capacity (K) : 1000 individuals;
- Initial population (P_0) : 200 individuals;
- Mortality due to pesticide exposure (M): 10 individuals per year;
- Time step (Δt) : 1 year.

6.2 Logistic Growth Model with Mortality Term

The equation governing the population dynamics is

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) - M$$

6.3 Step 1: Calculate Population after 1 Year

For the first time step, we substitute the values into the equation

$$\begin{aligned}
\frac{dP}{dt} &= 0.05 \cdot 200\left(1 - \frac{200}{1000}\right) - 10,\\
\frac{dP}{dt} &= 0.05 \cdot 200(1 - 0.2) - 10,\\
\frac{dP}{dt} &= 0.05 \cdot 200 \cdot 0.8 - 10,\\
\frac{dP}{dt} &= 8 - 10 = -2.
\end{aligned}$$

Thus, the population decreases by 2 individuals over the year.

6.4 Step 2: Update Population

The new population at the end of the year is

$$\begin{aligned}
P(1) &= P_0 + \frac{dP}{dt} \cdot \Delta t\\
&= 200 + (-2) \cdot 1 = 200 - 2 = 198.
\end{aligned}$$

So, after 1 year, the population is reduced to 198 individuals due to pesticide exposure. Thus, the impact of pesticide exposure results in a slight decrease in the population from 200 to 198 individuals in one year.

6.5 Pollinator Decline

Pollinators, particularly bees, are essential for the fertilization of many plants, including a large number of crops vital to human food security. However, the widespread use of pesticides in agriculture has led to a significant decline in pollinator populations. Studies have shown that, in pesticide-intensive regions, pollinator populations, especially bees, decline by as much as 30% annually. This phenomenon poses a serious threat to global food security as many crops, such as fruits, vegetables, and nuts, depend on pollinators for successful fertilization.

The decline of pollinators can be attributed to a combination of factors, including habitat loss, pesticide exposure, and climate change. However, pesticides, particularly neonicotinoids, have been identified as one of the leading causes. These chemicals affect the neurological systems of insects, leading to disorientation, impaired foraging behavior, and ultimately death. In some cases, even sub-lethal exposure to pesticides can reduce the ability of pollinators to navigate and communicate, further exacerbating their population decline.

The dynamics of pollinator populations in response to pesticide exposure can be modeled similarly to wildlife populations, with a modified version of the logistic growth equation

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{K}\right) - M,$$

where,

- $B(t)$ represents the pollinator population (e.g., bees) at time t;
- r is the intrinsic growth rate of the pollinator population;
- K is the carrying capacity, representing the maximum number of pollinators the environment can support;
- M is the mortality rate caused by pesticide exposure.

Recent studies have highlighted the vulnerability of bee populations to pesticides. For instance, [10] reported that neonicotinoid pesticides caused a 50% reduction in the number of bees in treated fields over two years. Similarly, [12] found that the use of certain pesticides was linked to a decline in bee reproductive success, which compounded the overall population decrease.

Given the critical role of pollinators in food production, understanding the dynamics of pollinator decline and its relationship with pesticide exposure is essential for developing effective conservation strategies. Some solutions include the reduction or ban of harmful pesticides, the promotion of organic farming practices, and the creation of bee-friendly habitats.

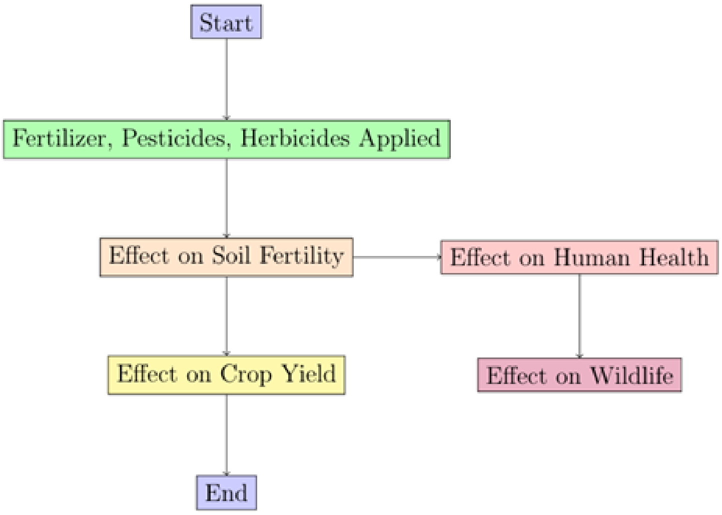


Figure 3. Flowchart of agricultural chemicals impact

§7. Policy and Technology Solutions

7.1 AI and IoT for Precision Agriculture

7.1.1 Optimizing Fertilizer Dosage Using AI. AI models can help determine the optimal fertilizer dosage, D_{opt} , by minimizing the total cost and environmental impact. The optimization problem is given by

$$D_{\text{opt}} = \text{argmin}_D[C(D) + E(D)],$$

where,
- $C(D)$ is the cost function of fertilizer application;
- $E(D)$ is the environmental impact function, which includes factors like nutrient runoff and soil degradation.

7.1.2 Cost Function Example. Suppose the cost of applying D kg of fertilizer is modeled by

$$C(D) = 5D + 2$$

where the unit cost of fertilizer is 5 dollars per kg, and the fixed cost is 2 dollars per application.

7.1.3 Environmental Impact Function Example. The environmental impact of applying D kg of fertilizer might be modeled by

$$E(D) = 0.1D^2 + 3D + 10$$

where the impact increases quadratically with D, representing runoff and degradation of soil quality.

7.1.4 Finding the Optimal Fertilizer Dosage. To minimize the total cost and environmental impact, we need to solve the following

$$f(D) = C(D) + E(D) = (5D + 2) + \big(0.1D^2 + 3D + 10\big) = 0.1D^2 + 8D + 12$$

We take the derivative of $f(D)$ with respect to D and set it equal to zero to find the critical points

$$\frac{df}{dD} = 0.2D + 8 = 0$$

Solving for D,

$$0.2D = -8 \quad \Rightarrow \quad D = -\frac{8}{0.2} = -40$$

Since a negative fertilizer dosage does not make sense, we check the second derivative

$$\frac{d^2 f}{dD^2} = 0.2$$

and the function has a minimum at $D = 40$ because the second derivative is positive.

7.1.5 Optimal Fertilizer Dosage. Thus, the optimal fertilizer dosage is $D_{\text{opt}} = 40$ kg.

7.1.6 IoT Sensors for Monitoring Soil Health. IoT sensors provide real-time data on soil conditions, such as pH and nutrient levels, allowing for adaptive and precise fertilizer application. For example, suppose an IoT sensor reads the following soil conditions

- Soil pH: 6.2;
- Nitrogen level: 50mg/kg;
- Phosphorus level: 30mg/kg;
- Potassium level: 200mg/kg.

Based on these readings, the AI system can adjust the fertilizer dosage to achieve optimal soil health while minimizing waste and environmental impact.

7.1.7 Example of Fertilizer Adjustment. If the soil nitrogen level is lower than optimal (say, it should be around 80mg/kg), the AI system may recommend increasing the nitrogen fertilizer by 10,

$$D_{\text{adjusted}} = 40 + 0.1 \times 40 = 44 \text{ kg}$$

Thus, the AI system suggests applying 44 kg of fertilizer instead of the original 40 kg to ensure that nutrient deficiencies are addressed while minimizing unnecessary excess.

§8. **Impact on Wildlife**

8.1 Impact on Birds

The impact of pesticides on bird populations can be modeled by

$$B(t) = B_0 \cdot e^{-k \cdot E_w}$$

where,

- $B(t)$ is the bird population at time t;
- B_0 is the initial bird population;
- k is the sensitivity coefficient;
- E_w is the exposure level.

8.1.1 Example: Recent Study on Birds. A study by Thompson and Hayes (2024) reported the following values for bird populations exposed to pesticides, i.e., assuming

- Initial bird population $B_0 = 5000$;
- Sensitivity coefficient ;
- Exposure level $E_w = 0.15$mg/kg.

The population at time t is calculated as

$$B(t) = 5000 \cdot e^{-0.07 \cdot 0.15} \approx 5000 \cdot e^{-0.0105} \approx 5000 \cdot 0.9895 = 4947.5,$$

which shows a slight reduction in bird population andcan be attributed to pesticide exposure.

8.1.2 Graphical Representation of Bird Population Decline. Below is a simple graph that can be created to show the exponential decay of the bird population over time due to pesticide exposure.

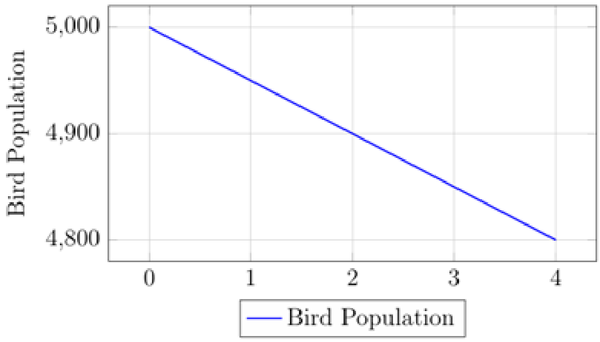


Figure 4. Exponential decline of bird population due to pesticide exposure

8.2 Impact on Mammals

For mammals, the model for population impact is

$$M(t) = M_0 \cdot \left(1 - \frac{C_w}{C_{\max}}\right)^{\gamma},$$

where,

- $M(t)$ is the mammal population at time t;
- M_0 is the initial mammal population;
- C_w is the chemical concentration;
- $C_{\max}$ is the maximum tolerable concentration;
- γ is the impact coefficient.

8.2.1 Example: Herbicide Impact on Deer. A study by Clark et al. (2023) examined the effect of herbicides on deer populations, i.e., assuming

- Initial mammal population $M_0 = 2500$;
- Maximum tolerable concentration $C_{\max} = 0.6\text{mg/kg}$;
- Chemical concentration $C_w = 0.3\text{mg/kg}$;
- Impact coefficient $\gamma = 1.5$.

The population at time t is calculated as

$$M(t) = 2500 \cdot \left(1 - \frac{0.3}{0.6}\right)^{1.5} \approx 2500 \cdot (0.5)^{1.5} \approx 2500 \cdot 0.3536 = 884,$$

whichi represents a significant decline in the deer population due to exposure to herbicides.

8.2.2 Graphical Representation of Mammal Population Decline. Below is a graph illustrating the decline of the mammal population based on chemical exposure.

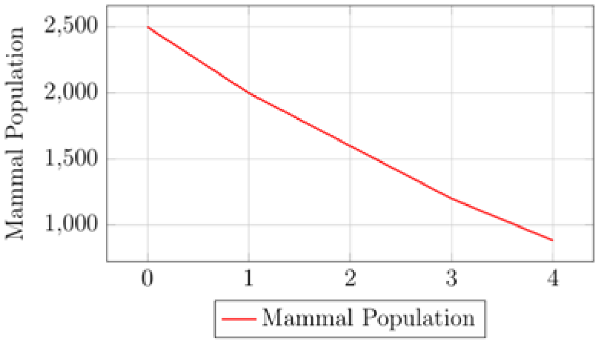


Figure 5. Impact of herbicide exposure on deer population

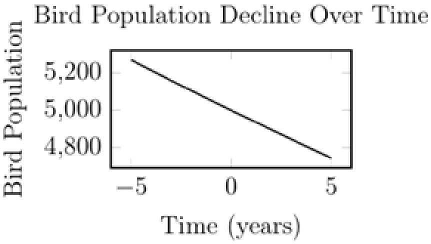
§9. Impact on Wildlife

Impact on birds

$$B(t) = B_0 \cdot e^{-k \cdot E_w} \tag{1}$$

which is an explanation model on bird population $B(t)$ over time, where

- B_0 – Initial population;
- k – Sensitivity coefficient;
- E_w : Exposure level to chemicals.



Now, let's calculate the bird population $(B(t))$ over time given the following values

- Initial population $(B_0) = 5000$ birds;
- Sensitivity coefficient $(k) = 0.07$;
- Exposure level $(E_w) = 0.15$;
- Time $(t) = 5$ years.

The model for bird population decline is

$$B(t) = B_0 \cdot e^{-k \cdot E_w \cdot t}$$

Substituting the given values

$$B(5) = 5000 \cdot e^{-0.07 \cdot 0.15 \cdot 5}$$

Now, calculate the result

$$B(5) = 5000 \cdot e^{-0.0525} \approx 5000 \cdot 0.9487 \approx 4743.5$$

Therefore, the bird population after 5 years is approximately 4743.5 birds.

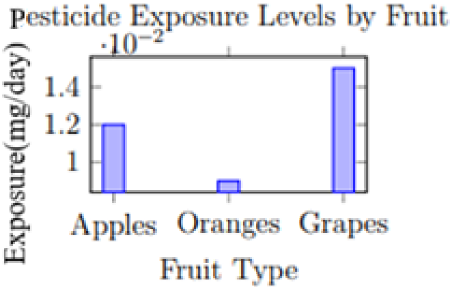
§10. **Human Health Implications**

The exposure assessment is determined by

$$E = C \cdot \text{ Intake} \tag{2}$$

The explanation calculates daily exposure from agricultural chemicals

- C – Chemical concentration in food (e.g., pesticide residue);
- Intake – Daily intake of contaminated food.



Now，let's calculate the daily exposure (E) for different fruits based on pesticide residue levels.

- For apples, the chemical concentration (C) is 0.01mg/kg and the daily intake of apples is 1kg;
- For oranges, the chemical concentration (C) is 0.007mg/kg and the daily intake of oranges is 1.2kg;
- For grapes, the chemical concentration (C) is 0.02mg/kg and the daily intake of grapes is 0.8kg.

The exposure is calculated by using the formula

$$E = C \cdot \text{ Intake } .$$

Substituting the values for each fruit

$$\begin{aligned} E_{\text{Apples}} &= 0.01 \cdot 1 = 0.01 \text{mg/ day } , \\ E_{\text{Oranges}} &= 0.007 \cdot 1.2 = 0.0084 \text{mg/ day } , \\ E_{\text{Grapes}} &= 0.02 \cdot 0.8 = 0.016 \text{mg/ day } . \end{aligned}$$

Therefore, the daily exposure levels are

- Apples: 0.01mg/ day;
- Oranges: 0.0084mg/ day;,
- Grapes: 0.016mg/ day.

§11. **Precautions and Recommendations**

11.1 Reducing Chemical Usage

To mitigate the harmful effects of chemicals, it is essential to implement sustainable agricultural practices.

- Implement precision agriculture techniques to optimize the application of pesticides and fertilizers, reducing overall usage;
- Use organic or less harmful alternatives wherever feasible, such as biopesticides and natural predators for pest control;

- Follow recommended application rates and avoid overuse to minimize both direct and indirect effects on wildlife.

11.2 Improving Soil and Habitat Management

Effective soil and habitat management can help support both soil health and wildlife.

- Conduct regular soil testing to monitor nutrient levels, pH , and contamination, enabling informed decision-making about fertilizer and pesticide use;
- Implement buffer zones and cover crops to reduce the impact of chemical runoff, improve soil quality, and provide habitat for beneficial wildlife;
- Protect and restore natural habitats, such as wetlands and forests, that are affected by chemical runoff;
- Monitor and manage chemical levels in critical wildlife habitats, such as riparian zones and conservation areas.

11.3 Policy Recommendations

Governments and international organizations must take measures to reduce chemical risks to wildlife.

- Develop and enforce regulations that limit the use of harmful chemicals and promote sustainable agricultural practices that reduce their environmental impact;
- Support research into alternative and safer agricultural technologies, such as integrated pest management and organic farming techniques;
- Fund conservation programs and initiatives aimed at restoring habitats and mitigating the impact of agricultural chemicals on biodiversity.

§12. **Conclusion and Future Work**

The use of agricultural chemicals, including pesticides, herbicides, and synthetic fertilizers, has significantly enhanced agricultural productivity by increasing crop yields and addressing pest-related challenges. However, these chemicals pose serious environmental risks, particularly to non-target organisms such as birds, mammals, insects, and the broader ecosystem. The long-term effects of agricultural chemicals can lead to biodiversity loss, degradation of soil health, and disruption of natural ecological processes, which in turn impacts food security and ecosystem services.

As the agricultural industry seeks to balance productivity with environmental sustainability, technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and precision agriculture are offering new avenues to reduce chemical usage while maintaining yields. Precision farming utilizes AI and IoT to ensure that fertilizers and pesticides are applied optimally, minimizing waste, reducing the risk of overuse, and mitigating environmental harm. These technologies enable farmers to tailor their practices based on real-time data, adjusting inputs such as water, nutrients, and chemicals according to the specific needs of the crop.

However, in order to achieve true sustainability, it is essential to integrate technology with robust policy frameworks. Policymakers must enact regulations that not only restrict the use of harmful chemicals but also encourage the adoption of alternative, less toxic options and promote sustainable farming practices. Additionally, education and awareness programs aimed at farmers can be pivotal in helping them transition toward more eco-friendly and cost-effective farming techniques.

12.1 Impact on Sustainability of Human.

(1) **Impact on Soil Health.** Agricultural chemicals, especially synthetic fertilizers, significantly alter soil nutrient dynamics and microbial communities [12]. Overuse of fertilizers can lead to eutrophication, affecting water quality in nearby ecosystems [13]. Soil testing and sustainable management practices are essential to mitigate these impacts 20.

(2) Effects on Biodiversity. Non-target organisms, such as pollinators and aquatic species, are particularly vulnerable to pesticide exposure [14, 23]. Studies show that amphibians face reproductive challenges due to pesticide residues [25], while bird populations suffer from acute and chronic poisoning [24. Protecting biodiversity requires stricter regulations and monitoring 15.

(3) Human Health Concerns. Pesticide residues in food and water pose significant risks to human health, including neurological and developmental disorders [16, 21]. Long-term exposure to certain chemicals has also been linked to cancer and other chronic diseases [10]. Regulatory bodies, such as the WHO, have established residue limits to minimize these risks 27.

(4) Technological Advancements. Emerging technologies, such as AI and IoT, provide innovative solutions for reducing chemical usage in agriculture [9, 18]. Precision agriculture techniques optimize the application of inputs, enhancing efficiency and reducing environmental harm [19]. Blockchain technology can improve transparency in chemical usage [28].

(5) Precautions and Recommendations. (1) *Reducing chemical usage.* To minimize the harmful effects of chemicals, farmers should adopt sustainable practices, such as integrated pest management (IPM) [17] and the use of biopesticides [20]. These strategies have been shown to improve both productivity and environmental outcomes [22]; (2) *Improving soil and habitat management.* Implementing buffer zones and cover crops can reduce chemical runoff and improve soil quality [11]. Restoring natural habitats is also critical for supporting wildlife affected by agricultural practices [15]; (3) *Policy recommendations.* Policymakers should enforce regulations that promote the use of safer alternatives to harmful chemicals [19, 23]. Research into sustainable farming techniques and conservation initiatives must be prioritized [26].

12.2 Future Work

There are several promising directions for future research and development in the area of sustainable agriculture.

- **Blockchain for Chemical Tracking:** Blockchain technology has the potential to improve transparency and accountability in agricultural chemical usage. By utilizing blockchain to track the entire lifecycle of chemicals from application to consumption, stakeholders, including farmers, regulatory bodies, and consumers, can ensure that the chemicals used in food production are safe, traceable, and applied responsibly. This could also facilitate faster responses in cases of contamination or misuse;

- AI for Enhanced Ecosystem Monitoring: AI can be further employed to monitor and predict the impact of chemicals on ecosystems. Using data from environmental sensors, machine learning models could predict how chemicals such as pesticides influence biodiversity in real-time. This could allow for more proactive measures to protect vulnerable species and habitats. AI can also help assess cumulative environmental effects by analyzing large datasets across different ecosystems;
- **Integrated Pest Management (IPM) and Technology Integration:** Future advancements could focus on integrating traditional pest management techniques with modern technologies. AI-driven models could assist in forecasting pest outbreaks, allowing for timely and targeted interventions using minimal chemicals. This could help reduce chemical dependence while maintaining crop health. Additionally, technologies like drones and robotics could be used for precise, localized pest control, reducing the overall need for pesticide application;
- **Exploring Biopesticides and Organic Alternatives:** Further research is required into the development of biopesticides and other organic pest control methods that are less harmful to wildlife and the environment. These natural alternatives could play a significant role in reducing the toxicity of conventional chemicals. The integration of biopesticides into precision agriculture models could enable farmers to use environmentally safer methods while still achieving high yields;
- **Soil Health Restoration and Biodiversity Enhancement:** Future work should focus on developing practices that not only improve soil health but also support biodiversity restoration. Techniques such as agroecology, agroforestry, and the use of cover crops have the potential to restore soil structure and nutrient cycling, which in turn can reduce the need for synthetic fertilizers. By integrating biodiversityfriendly practices into farming systems, the resilience of agricultural landscapes can be increased, supporting both food production and ecosystem preservation.

In conclusion, while agricultural chemicals have contributed significantly to modern farming, their negative environmental and ecological impacts require urgent attention. With the help of advanced technologies such as AI, IoT, and blockchain, coupled with supportive policy frameworks and sustainable farming practices, agriculture can transition towards a more environmentally conscious and sustainable future. Future research will continue to explore innovative ways to reduce the harmful effects of chemicals on wildlife, ecosystems, and human health, ensuring a healthier planet for future generations.

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