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INTERSYSTEMIC COMMUNICATION BETWEEN LAW, SCIENCE, AND ECONOMICS: A LEGAL-CRIMINAL ANALYSIS OF SOIL DAMAGE

COMUNICAÇÃO INTERSISTÊMICA ENTRE DIREITO, CIÊNCIA E ECONOMIA: UMA ANÁLISE JURÍDICO-PENAL DE DANOS AO SOLO

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Linia Dayana Lopes Machado*
*Universidade de Rio Verde (UNIRV), Rio Verde, Goiás, Brasil
Lattes: http://lattes.cnpq.br/2642744874617998
Orcid: https://orcid.org/0000-0002-7212-0525
liniadayana@unirv.edu.br

Leonel Severo Rocha**
**Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo, Rio Grande do Sul, Brasil
Lattes: http://lattes.cnpq.br/3283434447576859
Orcid: https://orcid.org/0000-0002-6971-1412
leonel.rocha@icloud.com

June Faria Scherrer Menezes*
*Universidade de Rio Verde (UNIRV), Rio Verde, Goiás, Brasil
Lattes: http://lattes.cnpq.br/1417663421283419
Orcid: https://orcid.org/0000-0002-8368-1803
june@unirv.edu.br

João Porto Silvério Júnior*
*Universidade de Rio Verde (UNIRV), Rio Verde, Goiás, Brasil
Lattes: http://lattes.cnpq.br/8323553235935271
Orcid: https://orcid.org/0000-0002-0633-9318
portosilverio@uol.com.br

Emanuel Victor de Moura Oliveira Barros*
*Universidade de Rio Verde (UNIRV), Rio Verde, Goiás, Brasil
Lattes: https://lattes.cnpq.br/8292182919930373
Orcid: https://orcid.org/0000-0002-5319-4385
emanuel@unirv.edu.br

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Abstract
The research investigates legal and criminal protection against soil damage caused by the use of phosphorus as a nutrient in agricultural production. It is based on Niklas Luhmann's Theory of Autopoietic Social Systems and its contemporary reinterpretations by Gunther Teubner and Leonel Severo Rocha, exploring intersystemic communication between law, economics, and science in the context of a globalized and hypercomplex society. The study is justified by the ability of Luhmann's Systems Theory to analyze ecological risks, considering that social systems operate in a self-referential manner but remain cognitively open. Soil, recognized by the United Nations as essential for agriculture and food security, requires effective

Resumo
A pesquisa investiga a proteção jurídico-penal contra os danos ao solo causados pelo uso de fósforo como nutriente na produção agrícola. Baseia-se na Teoria dos Sistemas Sociais Autopoiéticos de Niklas Luhmann e em suas reinterpretações contemporâneas por Gunther Teubner e Leonel Severo Rocha, explorando a comunicação intersistêmica entre direito, economia e ciência no contexto de uma sociedade globalizada e hipercomplexa. O estudo justifica-se pela capacidade da Teoria dos Sistemas de Luhmann em analisar riscos ecológicos, considerando que os sistemas sociais operam de forma autorreferencial, mas permanecem cognitivamente abertos. O solo, reconhecido pelas Nações Unidas como

protection in light of environmental challenges and the goals of the 2030 Agenda. The research proposes a systemic reinterpretation of environmental protection, investigating how the legal system deals with the (im)probability of intersystemic communication to operationalize legal and criminal protection against soil contamination by phosphorus. Methodologically, it is a descriptive study based on bibliographic and documentary research, using data from Hemielevski's study, which assesses the environmental risk of phosphate fertilization. The results confirm the hypothesis of structural coupling between the environmental and criminal legal subsystems to address soil contamination. It concludes that Article 54 of the Environmental Crimes Law (Law No. 9.605/98) provides the most appropriate protection against this degradation. The research recommends that the Rio Verde Environmental Secretariat develop a Normative Instruction to define the necessary documentation for environmental licensing, establish technical criteria for the application of phosphate fertilizers, and monitor soil quality in accordance with Hemielevski's guidelines.

Keywords: Systemic Theory. Society. Complexity. Environment. Criminal Law.

essencial para a agricultura e a segurança alimentar, requer proteção efetiva diante dos desafios ambientais e das metas da Agenda 2030. A pesquisa propõe uma reinterpretação sistêmica da proteção ambiental, investigando como o sistema jurídico lida com a (im)probabilidade da comunicação intersistêmica para operacionalizar a proteção jurídica e penal contra a contaminação do solo por fósforo. Metodologicamente, trata-se de um estudo descritivo baseado em pesquisa bibliográfica e documental, utilizando dados do estudo de Hemielevski, que avalia o risco ambiental da fertilização fosfatada. Os resultados confirmam a hipótese de acoplamento estrutural entre os subsistemas jurídico-ambiental e penal para lidar com a contaminação do solo. Conclui-se que o Artigo 54 da Lei de Crimes Ambientais (Lei nº 9.605/98) oferece a proteção mais adequada contra essa degradação. A pesquisa recomenda que a Secretaria de Meio Ambiente do Rio Verde elabore uma Instrução Normativa para definir a documentação necessária para o licenciamento ambiental, estabeleça critérios técnicos para a aplicação de fertilizantes fosfatados e monitore a qualidade do solo de acordo com as normas.

Palavras-chave: *Teoria Sistêmica. Sociedade. Complexidade. Meio Ambiente. Direito Penal.*

1 INTRODUCTION

The subsystems of Law, Science (Agronomy), and Economics require their own codification of autopoietic closure. The operability of Law, from an ecological perspective, depends on a key factor in communication: the distinction between the language of price (the economic system), the language of norms (the legal system), and the language of truth/untruth (the scientific system). This distinction is essential for intersystemic communication, which enables the pursuit of solutions that promote a more just and balanced society while taking ecological issues into account (Machado, 2021).

In this context, the binary codification of systems plays a fundamental role, as it allows the legal system to open itself to the influence of the social system and other partial systems. Such openness is only possible through operational closure, since the greater the degree of closure of a system, the more stable it becomes and the more suitable it is for

cognitive openness (Machado, 2021; Luhmann, 2016). In this way, Law can structure its interactions with other subsystems without losing its functional identity.

Intersystemic communication among economic, scientific, and legal subsystems requires a structural and normative design that ensures its effectiveness. Law is shaped in accordance with economic and scientific aspirations and is maintained through communication, which depends on language, function, differentiation, and structures, resulting in the evolution of society. Thus, the promotion of mechanisms of intersystemic communication among Law, Economics, and Science (Agronomy) becomes essential both for the advancement of academic research and for the development of solutions that enable sustainable environmental protection (Teubner, 1989; Machado, 2021).

The interaction between Law and Economics, in turn, must be analyzed in light of the challenges posed by technology and risk management. Legal protection of environmental assets in a context of accelerated technological advancement makes the improbability of communication between systems a particularly relevant theoretical issue. The interaction between the legal and economic systems must produce effects that promote the proper management of future risks without hindering development, avoiding the imposition of excessively prohibitive norms. In this sense, in response to global expectations regarding Law, modern state constitutions emerge as structural mechanisms of transversal rationality among Law, Economics, Science, and Politics (Rocha, 2000; Machado, 2021).

In this scenario, the following research problem is formulated: how can the legal system address the (im)probability of intersystemic communication among Law, Science, and Economics as a procedure for operationalizing legal-criminal protection against soil contamination caused by the addition of phosphorus as a nutrient in agricultural production, in light of the risks produced in contemporary complex society?

Accordingly, the general objective of this study is to offer a systemic reinterpretation of legal-criminal protection against damage to soil caused by the addition of phosphorus as a nutrient in agricultural production. The focus lies on the possibility of intersystemic communication among Law, Economics, and Science within the context of a complex society, characterized by functional fragmentation and a hypercomplex environment. To this end, the study is grounded in Niklas Luhmann’s pragmatic-systemic

theory and its contemporary reinterpretations, especially the contributions of Gunther Teubner and Leonel Severo Rocha.

Methodologically, the research is descriptive and qualitative in nature, based on bibliographic and documentary research. Classical and contemporary works on Social Systems Theory are analyzed, as well as normative texts of Brazilian Environmental and Criminal Law, with particular emphasis on Law No. 9,605/1998. In addition, technical-scientific data from agronomic studies are employed, especially the research conducted by Hemielevski, which assesses the environmental risks arising from phosphate fertilization, thereby enabling the observation of the possibility of structural coupling among the legal, scientific, and economic subsystems in the operationalization of environmental protection of soil.

2 INTERSYSTEMIC COMMUNICATION BETWEEN LAW, ECONOMICS, AND SCIENCE IN THE CONTEXT OF COMPLEX SOCIETY

Communication is a fundamental element of contemporary society and a decisive factor in the integration of social systems. For Niklas Luhmann, communication occurs through a process of functional differentiation, in which social systems organize themselves autonomously while maintaining intersystemic interactions. Law, Economics, and Science are paradigmatic examples of subsystems that, despite operating according to distinct logics, establish relationships of interdependence in the formulation of responses to complex social problems (Luhmann, 1993).

In the context of modern societies, the fragmentation of global regulatory regimes and the radicalization of functional differentiation challenge traditional models of legal regulation. The autopoiesis of social systems implies that each system operates according to its own internal logic and binary code, which generates structural obstacles to normative harmonization across different fields of knowledge. Consequently, the relationship among Law, Economics, and Science must be understood in light of the intrinsic complexity of each of these systems and of the limits imposed on their mutual communication (Rocha, 2018).

Legal responses to environmental issues, for instance, depend directly on the interface among these subsystems. The use of arable land and the ecological risks arising

from intensive agricultural exploitation require scientific knowledge to identify and assess environmental impacts, economic analysis to evaluate the feasibility and costs of mitigation measures, and legal regulation to establish binding norms, responsibilities, and sanctions. This form of structural coupling enables each system to remain operationally closed while being cognitively open to relevant communications from other systems, thereby enhancing the effectiveness of environmental governance (Teubner, 2020).

In this sense, intersystemic communication functions as a mechanism that allows legal systems to adapt and evolve in response to the challenges posed by complex society. Law can no longer be analyzed solely through the lens of traditional legal dogmatics; rather, it must be understood as a dynamic social system that responds to external irritations—originating from economic pressures and scientific knowledge—through regulatory adjustments and normative innovations (Rocha, 2020).

The contemporary risk society further intensifies the need for efficient and interconnected interactions among Law, Economics, and Science. Issues such as sustainable development and environmental protection clearly illustrate this demand for dialogue, as the success of public policies in these areas depends on the synergy among social subsystems. In this regard, Luhmann's systems theory provides a relevant analytical framework for understanding, evaluating, and improving intersystemic communication, thereby contributing to more coherent and effective regulatory responses to the complex risks of modern society (Luhmann, 2007).

3 INTERSYSTEMIC COMMUNICATION BETWEEN LAW, ECONOMICS, AND SCIENCE IN THE CONTEXT OF COMPLEX SOCIETY

Communication constitutes a foundational element of contemporary society and a decisive factor for the integration, coordination, and evolution of social systems. Within Niklas Luhmann's theoretical framework, communication is understood not as a mere exchange of information between actors, but as the basic operation through which social systems are constituted and reproduced. Social systems emerge and persist through communicative processes that follow specific internal logics, resulting in a structure of functional differentiation in which systems such as Law, Economics, and Science operate autonomously while remaining mutually observable (Luhmann, 1993; Luhmann, 2007).

In this differentiated social order, each subsystem is characterized by a specific binary code that guides its operations: legal/illegal in Law, payment/non-payment in Economics, and true/false in Science. These codes ensure operational closure, allowing systems to maintain their identity and internal coherence. At the same time, however, no system exists in isolation. Complex social problems—particularly those involving environmental risks, technological innovation, and economic development—generate external irritations that require systems to engage in intersystemic communication. Such communication does not eliminate systemic boundaries but rather occurs through selective translations that preserve functional autonomy while enabling coordinated responses (Luhmann, 1993; Teubner, 1989).

In the context of modern societies, the fragmentation of global regulatory regimes and the intensification of functional differentiation challenge traditional, state-centered models of legal regulation. Law no longer occupies a hierarchical position capable of unilaterally steering social behavior across all domains. Instead, it must operate within a polycentric and pluralistic environment, characterized by overlapping normative orders and competing rationalities. The autopoietic nature of social systems implies that each system reproduces itself according to its own internal logic, rendering direct normative harmonization among Law, Economics, and Science highly improbable (Rocha, 2018; Teubner, 1997).

This structural condition becomes particularly evident in the field of environmental protection. Legal responses to ecological problems depend fundamentally on intersystemic interfaces. Scientific knowledge is essential for identifying environmental impacts, establishing risk thresholds, and providing empirical evidence of ecological degradation. Economic rationality, in turn, evaluates the feasibility, costs, and incentives associated with environmental policies and mitigation measures. Law translates these scientific and economic communications into normative expectations, binding rules, and enforcement mechanisms. This process of structural coupling enables each subsystem to contribute according to its own rationality, while collectively addressing complex environmental challenges (Teubner, 2020; Luhmann, 2007).

The management of agricultural soils and the ecological risks arising from intensive land use exemplify this dynamic. Scientific studies assess soil contamination, nutrient cycles, and long-term environmental impacts; economic analysis examines

productivity, cost-efficiency, and market pressures; and legal norms establish standards of environmental protection, licensing requirements, and criminal liability. Without effective intersystemic communication, legal regulation risks either becoming symbolically ineffective or excessively restrictive, failing to balance environmental protection with economic development (Rocha, 2020; Machado, 2021).

From this perspective, intersystemic communication serves as a key mechanism for the adaptive capacity and evolutionary potential of legal systems in complex societies. Law can no longer be adequately understood solely through the lens of traditional legal dogmatics, which presupposes coherence, hierarchy, and centralized control. Rather, it must be conceptualized as a reflexive and learning-oriented system, capable of responding to external irritations through regulatory experimentation, proceduralization, and the incorporation of scientific and economic knowledge into its normative frameworks (Teubner, 1989; Rocha, 2020).

The contemporary risk society further intensifies the demand for efficient and interconnected interactions among Law, Economics, and Science. Ulrich Beck's notion of risk society underscores how modern risks—often invisible, transboundary, and scientifically mediated—cannot be effectively managed by any single social system in isolation. Sustainable development, climate change governance, and environmental protection thus require continuous dialogue and coordination among subsystems, as the success of public policies in these areas depends on the alignment of scientific evidence, economic incentives, and legal norms (Beck, 1992; Luhmann, 2007).

In this sense, Luhmann's systems theory provides a robust and analytically sophisticated framework for understanding intersystemic communication in contemporary society. By emphasizing operational closure, cognitive openness, and structural coupling, this theoretical approach offers valuable insights into how Law, Economics, and Science can interact without sacrificing their functional autonomy. Consequently, it contributes to the development of more coherent, effective, and sustainable regulatory responses to the complex risks that characterize modern social life (Luhmann, 1993; Teubner, 2020; Rocha, 2018).

3.1 Niklas Luhmann's Systems Theory and its application to law

Niklas Luhmann's Systems Theory represents an innovative and influential approach to understanding Law in contemporary society. In contrast to traditional normativist and hermeneutic theories, Luhmann advances a constructivist perspective in which Law is conceived as an autopoietic system—that is, a system that reproduces itself internally through its own operations and distinctions. This model emphasizes the relative autonomy of Law in relation to other social subsystems, while simultaneously acknowledging its structural connections with its external environment (Luhmann, 1993).

From this perspective, Law is not merely a reactive mechanism that applies pre-established norms, but a system that constructs and maintains its own structure through binary coding, such as legal/illegal. This means that the legal system does not operate according to external criteria of truth, morality, or justice, but rather according to internally generated criteria that ensure its coherence, stability, and continuity over time. Such an approach significantly reshapes the understanding of legal normativity, highlighting its evolutionary, adaptive, and self-referential character (Rocha, 2005).

In the environmental context, Systems Theory provides a powerful analytical framework for examining how Law interacts with Science and Economics in the formulation of sustainability-oriented norms. When the legal system processes scientific information about environmental risks—such as pollution, climate change, or soil degradation—it does not simply absorb this knowledge directly. Instead, it translates scientific communications into legal categories and normative expectations, adapting its internal structures to incorporate new regulatory standards aimed at constraining economically harmful practices. In this way, Law not only regulates external behavior but also transforms itself in response to emerging social and ecological demands (Teubner, 2011).

The functional differentiation of globalized society further requires that Law be capable of managing multiple and overlapping forms of complexity. The paradigm of legal autopoiesis implies that legal norms are produced according to the internal logic of the legal system, yet they must remain communicatively linked to other subsystems in order to maintain legitimacy and practical effectiveness. This balance between operational closure and cognitive openness is particularly crucial in addressing contemporary

challenges such as climate change, environmental degradation, and the ecological consequences of industrial and agricultural development (Rocha, 2018).

Accordingly, the application of Systems Theory to Law enables a deeper understanding of how legal norms are created, interpreted, and applied within a network of dynamic intersystemic interactions. Law should not be conceived as a static or isolated system, but as a continuously evolving field shaped by scientific advances, economic pressures, and social transformations. Luhmann's theoretical framework thus offers a robust conceptual foundation for analyzing the evolution of legal norms and institutions in response to the complex and rapidly changing conditions of contemporary society (Luhmann, 2007).

3.2 Social constitutionalism and the legal protection of the environment

Social constitutionalism emerges as a response to the profound transformations experienced by contemporary societies, particularly those related to social inequality, technological advancement, and environmental degradation. By expanding the scope of constitutional law beyond classical liberal rights, social constitutionalism seeks to adapt the constitutional framework to collective interests and structural vulnerabilities. Within this paradigm, environmental protection is elevated to the status of a fundamental right and a constitutional value, becoming an essential component of the normative architecture of modern states. This shift reflects the understanding that a healthy environment is a necessary condition for human dignity, social justice, and the full realization of other fundamental rights (Rocha, 2018).

The constitutionalization of environmental protection represents a qualitative transformation in the role of Law. Rather than treating environmental issues as merely regulatory or administrative concerns, constitutions increasingly recognize ecological integrity as a legal good deserving the highest level of protection. In the Brazilian constitutional order, for instance, Article 225 of the Federal Constitution establishes the right to an ecologically balanced environment and imposes shared duties on the State and society to defend and preserve it. This normative choice reinforces the principle of intergenerational responsibility, according to which present generations hold the

environment in trust for future ones, thereby incorporating long-term ecological considerations into constitutional decision-making (Canotilho, 2012).

Intergenerational responsibility challenges traditional legal conceptions centered on immediacy and individual interests. Environmental harm often manifests cumulatively and over extended periods, making it incompatible with short-term regulatory approaches. Social and environmental constitutionalism, therefore, demands preventive and precautionary legal strategies capable of addressing uncertainty and irreversible damage. Principles such as prevention, precaution, and sustainable development gain constitutional relevance, guiding legislative, administrative, and judicial actions toward the protection of ecological systems and natural resources (Carvalho, 2021).

The transition toward an Environmental Rule of Law also requires a reconfiguration of legal paradigms to address the complexity of ecological risks. Contemporary societies face global challenges such as climate change, pollution, deforestation, soil degradation, and biodiversity loss, which are intrinsically linked to industrialization and economic growth. In this context, Environmental Law must be understood as a dynamic and adaptive system that continuously incorporates scientific knowledge and risk assessments into legal decision-making. The law no longer operates solely through rigid commands and prohibitions, but increasingly through flexible regulatory instruments, impact assessments, and participatory governance mechanisms (Teubner, 2020).

Furthermore, environmental constitutionalism highlights the limits of state-centered regulation in an increasingly interconnected world. Environmental problems routinely cross national borders, rendering purely domestic legal solutions insufficient. As a result, international cooperation and transnational legal frameworks play a crucial role in environmental protection. Treaties, conventions, and international environmental regimes contribute to the harmonization of norms and standards, influencing domestic constitutional interpretation and legislative reform. This multilevel governance structure strengthens environmental protection by fostering coordination among states and aligning national policies with global sustainability objectives (Wedy, 2021).

Judicialization also assumes particular importance within social and environmental constitutionalism. Courts are increasingly called upon to enforce constitutional environmental rights, assess the legality of public policies, and resolve conflicts between

economic development and environmental protection. Through constitutional review and the application of environmental principles, the judiciary contributes to shaping the content and effectiveness of environmental norms, reinforcing the binding nature of constitutional commitments to sustainability and ecological balance (Carvalho, 2021).

In this sense, social and environmental constitutionalism represents a significant evolution in legal thought, redefining the relationship between Law, society, and nature. By embedding environmental protection within constitutional frameworks, this model enhances environmental governance, legitimizes public intervention in defense of ecological interests, and promotes a balanced integration of economic development and environmental preservation. Ultimately, it provides a normative foundation for pursuing sustainable development and ensuring a viable and equitable future for present and future generations.

4 ENVIRONMENTAL IMPACTS AND LEGAL REGULATION OF RIBEIRÃO ABÓBORA

Ribeirão Abóbora is the main water supply source for the municipality of Rio Verde, in the state of Goiás, Brazil, serving both human consumption and agro-industrial activities. The strategic importance of this watercourse makes its protection and efficient management essential to ensure water security for the local population and economic sectors dependent on this resource. However, the intensification of agricultural and livestock activities in the region has led to a significant increase in phosphorus concentrations in the soil, directly affecting the water quality of Ribeirão Abóbora and accelerating eutrophication processes within the watershed (Hemielevski, 2019).

Eutrophication occurs as a result of excessive nutrient loading—particularly phosphorus—into aquatic ecosystems, leading to the uncontrolled growth of algae and cyanobacteria. This phenomenon reduces light penetration in the water column, impairs photosynthetic activity, and decreases dissolved oxygen levels, thereby compromising aquatic biodiversity and deteriorating water quality for human consumption. Empirical studies conducted in the Ribeirão Abóbora micro-basin reveal that several rural properties exhibit soil phosphorus levels exceeding environmentally acceptable thresholds,

highlighting the urgent need for effective nutrient management and environmental control measures to ensure the long-term sustainability of the region (Sharpley *et al*., 2003).

In light of these environmental risks, the implementation of robust regulatory mechanisms becomes imperative. Brazilian environmental legislation provides a comprehensive framework for the management and protection of water resources, particularly through the National Water Resources Policy (Law No. 9,433/1997) and the National Environmental Policy (Law No. 6,938/1981). These legal instruments establish principles and guidelines for the sustainable use of water, pollution control, and integrated watershed management. They also impose requirements such as water abstraction permits, environmental licensing, and systematic monitoring of water quality, aiming to prevent degradation and ensure the multiple uses of water resources (Brazil, 1997).

The analysis of soil contamination in rural properties within the Ribeirão Abóbora micro-basin further underscores the need for enhanced regulatory oversight regarding fertilizer use and the adoption of best agricultural practices. The excessive application of phosphate fertilizers can be mitigated through sustainable soil management strategies, including crop rotation, precision agriculture, nutrient budgeting, and the use of technologies that improve nutrient uptake efficiency. In addition, public policies focused on the restoration of degraded areas and the rehabilitation of riparian zones should be prioritized by environmental authorities as a means of reducing diffuse pollution and improving ecosystem resilience (Gatiboni *et al*., 2014).

Therefore, the protection of Ribeirão Abóbora requires an integrated and interdisciplinary approach involving rural producers, environmental agencies, policymakers, and the scientific community. Environmental regulation must be strengthened through policies that incentivize sustainable agricultural practices, promote environmental education, and support the recovery of degraded ecosystems. Moreover, the adoption of participatory environmental governance mechanisms—such as watershed committees and stakeholder engagement processes—can enhance regulatory effectiveness and foster shared responsibility for environmental stewardship. Such an approach is essential to ensure that Ribeirão Abóbora continues to meet the water needs of the population of Rio Verde while preserving its ecological integrity and long-term sustainability (Wedy, 2018).

5 METHODOLOGY

This research adopted a descriptive and exploratory design, aimed at describing existing phenomena and investigating still underexplored aspects of soil contamination by phosphorus in agricultural areas of the municipality of Rio Verde, Goiás, Brazil. The study employed a mixed-methods approach, combining qualitative and quantitative perspectives, and was based on the analysis of secondary data obtained from official documents, bibliographic references, and previously conducted technical and scientific studies related to the topic (Creswell, 2017; Flick, 2018).

The methodological choice for a descriptive–exploratory approach is justified by the need to systematize existing empirical and normative knowledge while identifying gaps in the legal and environmental regulation of phosphorus use in agriculture. The qualitative dimension focused on the interpretation of legal norms, policy frameworks, and theoretical contributions from environmental law and systems theory, whereas the quantitative dimension relied on the analysis of technical data regarding phosphorus concentrations in soils and their environmental implications.

The study was developed in two main phases. In the first phase, previously conducted mathematical modeling and laboratory analyses were used to assess the presence, retention, and behavior of phosphorus in agricultural soils. The calculations and experimental procedures were originally carried out by Hemielevski (2020) in research on the Environmental Critical Limit of Phosphorus (ECL-P), and their results were employed as secondary data in the present study. The ECL-P represents the threshold concentration of phosphorus beyond which its accumulation in soil poses a significant environmental risk, particularly with regard to nutrient runoff and water contamination (Hemielevski *et al.*, 2015).

To estimate phosphorus adsorption capacity and environmental risk, Hemielevski's study applied the Langmuir adsorption model (Langmuir, 1918), which is widely used to describe the interaction between phosphorus and soil particles. This model allows for the estimation of the maximum adsorption capacity of soils and the point at which phosphorus saturation increases the likelihood of leaching and transport to surface and groundwater bodies. The adoption of this model provides a scientifically validated

basis for evaluating the environmental vulnerability of agricultural soils within the Ribeirão Abóbora micro-basin.

In the second phase, the results obtained from the agronomic and environmental analyses were systematically examined from a legal and regulatory perspective. Brazilian environmental and criminal legislation, particularly the National Environmental Policy (Law No. 6,938/1981), the National Water Resources Policy (Law No. 9,433/1997), and the Environmental Crimes Law (Law No. 9,605/1998), were analyzed to assess their adequacy in addressing soil contamination and diffuse pollution caused by excessive phosphorus fertilization. This phase also involved a doctrinal analysis grounded in Systems Theory, seeking to identify possibilities of structural coupling between the legal, scientific, and economic subsystems in the operationalization of environmental protection.

By integrating scientific data with legal analysis, the methodology enabled a comprehensive understanding of phosphorus-related soil contamination as both an environmental and juridical issue. This interdisciplinary approach supports the identification of regulatory gaps and contributes to the formulation of recommendations aimed at strengthening environmental governance and promoting sustainable agricultural practices in the region. For this purpose, the Langmuir adsorption model (1918) was employed, which is defined by the following equation:

$$Q = \frac{Q_{max} K C}{1 + K C} \qquad (1)$$

where:

= amount of phosphorus adsorbed (mg/kg);
= maximum phosphorus adsorption capacity (mg/kg);
= adsorption affinity constant (L/mg);
= equilibrium concentration of phosphorus in the soil solution (mg/L).

The determination of available phosphorus content in the soil was carried out using the Mehlich 1 method (Mehlich, 1953), which consists of extracting phosphorus with a

solution of sulfuric acid and hydrochloric acid at a concentration of 0.025 mol/L. The equation used to calculate the available phosphorus in the soil was as follows:

$$P_{solúvel} = \frac{C_{amostra} \times V_{extrator}}{M_{solo}} \qquad (2)$$

where:

= concentration of extracted phosphorus (mg/kg);
= phosphorus concentration measured in the extracted solution (mg/L);
= volume of the extracting solution used (mL);
= mass of the soil sample used (g).

The experiments conducted by Hemielevski included the incubation of soil samples for 30 days prior to chemical extraction in order to ensure a more accurate assessment of phosphorus–soil interactions.

In the second phase, the research employed Niklas Luhmann's systemic approach (Luhmann, 1995) to analyze how different fields of knowledge—Law, Science, and Economics—interact in the environmental regulation of phosphorus in soil. This meant that the study was not limited to the technical aspects of contamination, but also sought to understand how legal norms, scientific advances, and economic interests influence policies for the control and management of this nutrient in agricultural practices.

The literature review was based on an in-depth exploration of the theoretical and conceptual framework related to the subject, enabling a comprehensive understanding of the main scientific, normative, and environmental approaches to phosphorus dynamics in soil. In parallel, the documentary research critically examined a wide range of scientific reports, environmental regulations, and preexisting technical studies, with particular emphasis on the empirical data from Hemielevski's research on the Environmental Critical Limit of Phosphorus for soils in the Brazilian Cerrado biome.

Data triangulation was employed to ensure greater reliability and robustness of the research findings. This method combined three primary sources of data: (i) experimental data obtained from laboratory analyses; (ii) bibliographic data providing theoretical and historical support regarding soil phosphorus dynamics and its legal regulation; and (iii)

documentary data derived from reports issued by environmental institutions and from current regulatory frameworks governing phosphorus use in agriculture.

Triangulation was essential to achieving the general objective of the study, as it enabled a holistic perspective on the problem. The analysis of laboratory data provided a basis for understanding phosphorus behavior in soils and the associated risks of water contamination. The application of mathematical models was fundamental for establishing environmentally safe thresholds and for supporting recommendations aimed at the formulation and improvement of public policies for environmental regulation in the municipality of Rio Verde, Goiás, Brazil.

6 RESULTS AND DISCUSSIONS

The research demonstrated that criminal-law protection against environmental damage to soil caused by phosphorus contamination in agricultural production depends on effective coordination between Environmental Law and Criminal Law. The study revealed that, although Brazil has specific legal frameworks aimed at soil protection—such as the Environmental Crimes Law (Law No. 9,605/1998) — there are significant gaps in the effective enforcement of sanctions and in the control of diffuse pollution resulting from the excessive use of phosphate fertilizers (Machado, 2021).

In Brazil, the legal protection of soil is addressed through several legislative instruments, including the Environmental Crimes Law (Law No. 9,605/1998), whose Article 54 criminalizes conduct that causes environmental pollution capable of resulting in harm to human health, fauna, and flora (Brazil, 1998); the National Environmental Policy Act (Law No. 6,938/1981), which establishes guidelines for natural resource management and environmental liability (Brazil, 1981); and the Forest Code (Law No. 12,651/2012), which regulates the sustainable use of land in areas of permanent preservation and legal reserves (Brazil, 2012).

However, the research showed that these legal instruments do not specifically address the impacts of excessive phosphorus fertilization, which hinders effective monitoring and the criminal and administrative accountability of the agents involved. The criminal classification of soil contamination by nutrients remains imprecise, failing to

distinguish the impacts of phosphorus from those caused by other contaminants, such as heavy metals and industrial toxic waste (Rocha, 2018).

The study also compared Brazilian legislation with international regulatory models, particularly Directive 2008/99/EC of the European Union, which addresses environmental protection through criminal law. Unlike the Brazilian framework, this directive explicitly defines environmental crimes related to soil pollution and directly assigns liability to those who exceed legally established limits for the application of chemical substances in agriculture (Teubner, 2020).

The application of Article 54 of the Brazilian Environmental Crimes Law to cases of soil contamination by phosphorus is particularly complex, as it requires proof of risk to public health or irreversible environmental damage—criteria that are often difficult to demonstrate in cases of diffuse pollution. To enhance the effectiveness of criminal-law protection, legislative improvement would be necessary, including the explicit criminalization of soil contamination caused by excessive nutrient inputs as a specific offense (Canotilho & Leite, 2012).

From the perspective of Niklas Luhmann's systems theory, environmental and criminal legislation operate as relatively autonomous subsystems but communicate through processes of structural coupling. The research demonstrated that effective soil protection depends on strengthening these interconnections between normative subsystems (Luhmann, 1997).

Structural coupling between the subsystems of Criminal Law and Environmental Law could be achieved through: (i) the creation of a specific criminal offense for soil contamination by phosphorus, ensuring greater precision in legal application and reducing reliance on complex evidentiary requirements (Rocha & Costa, 2018); (ii) the incorporation of technical criteria derived from agronomic science to define acceptable phosphorus levels in soil, thereby ensuring legal certainty in enforcement (Beck, 2011); and (iii) the expansion of environmental monitoring with the participation of scientific institutions, allowing technical data to support judicial decisions regarding criminal and administrative liability (Prittwitz, 2004).

The case of the municipality of Rio Verde, Goiás, demonstrated that the absence of specific local regulation significantly hinders the enforcement of environmental and criminal legislation. The research suggests that the Municipal Department of the

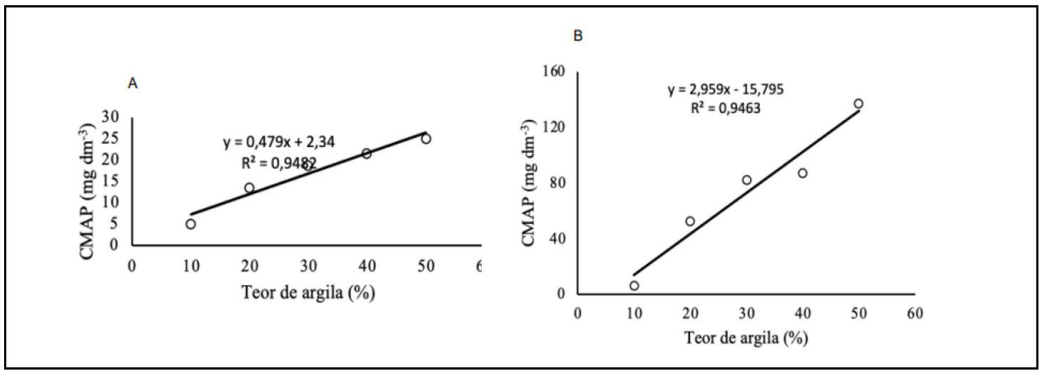
Environment of Rio Verde should issue a Normative Instruction establishing clear requirements for the inspection and control of phosphate fertilizer application, similar to existing regulatory frameworks for agricultural pesticides (Machado, 2021).

Experimental analyses conducted in the Ribeirão Abóbora micro-basin indicated that most of the soils evaluated exhibit phosphorus levels above the Environmental Critical Limit (ECL-P), thereby requiring urgent regulatory intervention. Phosphorus concentrations were determined using the Mehlich 1 extraction method, revealing that a substantial proportion of samples exceeded the recommended values for agricultural soils, which increases the likelihood of diffuse pollution of nearby water bodies. Moreover, the low Phosphorus Buffering Capacity (PBC) observed in some samples indicates a heightened risk of phosphorus mobilization following fertilizer application and its subsequent transport to aquatic systems.

Figure 1 illustrates the distribution of phosphorus levels in soils within the micro-basin, showing that approximately 40% of the samples presented values above 30 mg dm^{-3}, which constitutes a significant environmental risk if appropriate management practices are not implemented. Analysis of the relationship between clay content and phosphorus adsorption revealed that soils with lower clay content have a reduced capacity to retain the nutrient, making them more susceptible to leaching and surface runoff. Conversely, soils with higher clay content demonstrated greater stability in phosphorus retention, as evidenced by ECL-P calculations based on the equation ECL-P = 20 + 0.5 × % clay. These findings reinforce the need for regulatory policies that consider not only the quantity of fertilizer applied but also the adsorption capacity of soils, in order to effectively mitigate environmental impacts.

Figure 1

Increase in the maximum phosphorus adsorption capacity (MPAC) as a function of soil clay content. Addition of 0 to 20 mg dm⁻³ of P (A) and 40 to 120 mg dm⁻³ of P (B).



Source: Adapted from Hemielevski, 2020.

In light of these results, it is essential for environmental regulation to incorporate more refined technical criteria for the use of phosphate fertilizers, taking into account factors such as the Phosphorus Buffering Capacity (PBC) and the Maximum Phosphorus Adsorption Capacity (MPAC) of soils. The implementation of strategies such as continuous monitoring of soil phosphorus levels and the mandatory adoption of sustainable management practices can significantly reduce the risks of environmental contamination. Furthermore, the use of mathematical models, such as the Langmuir adsorption model, can assist in establishing more accurate limits for phosphorus application in agriculture, thereby ensuring a balance between agricultural productivity and environmental preservation.

The research also demonstrated that prevention should constitute the central focus of public and legal policies. Instruments such as environmental certification schemes (e.g., ISO 14001, Rainforest Alliance, among others) can contribute to the internalization of good agricultural practices, reducing reliance on criminal sanctions by encouraging sustainable soil management and proactive environmental responsibility (Carvalho, 2020).

Moreover, the incorporation of environmental compliance mechanisms within the agribusiness sector emerges as a viable pathway to prevent soil contamination. Corporate accountability models inspired by European environmental law could be integrated into the Brazilian legal system, ensuring that large-scale producers are held responsible for the

environmental impacts of their agricultural practices. Such mechanisms would strengthen environmental governance, promote risk prevention, and foster a culture of sustainability within agricultural production chains (Wedy, 2021).

7 CONCLUSION

The present research demonstrated the increasing complexity of the relationship between economic development and environmental sustainability. Based on the analysis of the impacts of soil contamination in the municipality of Rio Verde, Goiás, Brazil, the urgent need for integration between environmental law and criminal law became evident in order to ensure the protection of natural resources and minimize ecological risks. The advance of modernization has imposed significant challenges on environmental preservation, making the strengthening of environmental regulation and enforcement imperative.

The interaction among the legal, scientific, and economic subsystems proved to be fundamental for the construction of a more effective normative framework. The systemic approach allows for an understanding that law, in establishing norms and sanctions, cannot operate in isolation but must continuously engage with scientific advances and economic dynamics. The concept of the risk society, as analyzed throughout the study, reinforces the idea that environmental challenges are not merely local in nature, but rather entail global implications, thus requiring coordinated actions at different institutional levels.

In the context of phosphorus use as a polluting nutrient, it was identified that the absence of stricter regulations may lead to irreversible damage to soil and water quality. The research indicated that, despite the existence of environmental norms, the lack of effective oversight and of more detailed technical criteria has contributed to environmental degradation. In this regard, the implementation of more robust measures to monitor and control the use of this agricultural input is strongly recommended.

Another central point addressed in the study was the importance of intersystemic communication for the formulation of more effective public policies. Reflexive law, by considering the interaction among different subsystems, provides a theoretical foundation for understanding the need for an integrated approach to environmental regulation. Accordingly, environmental normativity must be aligned with scientific knowledge and

sustainable economic practices, with the aim of mitigating the negative impacts of technological progress.

Furthermore, the research emphasized that environmental criminal law must be strengthened to ensure that environmental offenses are properly sanctioned and that those responsible for environmental damage are held accountable for their actions. The possibility of non-prosecution agreements may serve as a useful instrument to encourage more responsible corporate behavior, provided that such mechanisms are applied under strict criteria and supported by sound technical evidence.

In light of the analyzed scenario, it becomes clear that environmental preservation cannot be treated as an isolated issue, but rather as an integral component of a sustainable development model. To this end, it is necessary for all involved actors—including public authorities, the productive sector, and civil society—to act in a coordinated and transparent manner, promoting a balance between economic growth and environmental protection.

This study contributes to broadening the debate on the need for a more dynamic and responsive legal model capable of addressing contemporary environmental challenges. Based on the reflections presented, it reinforces the importance of adopting public policies that integrate different fields of knowledge and promote sustainable practices. Only through such an approach will it be possible to ensure a balanced and ecologically viable future for future generations.

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