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Perspective

Muddied Waters: The Use of "Residual" And "Legacy" Phosphorus

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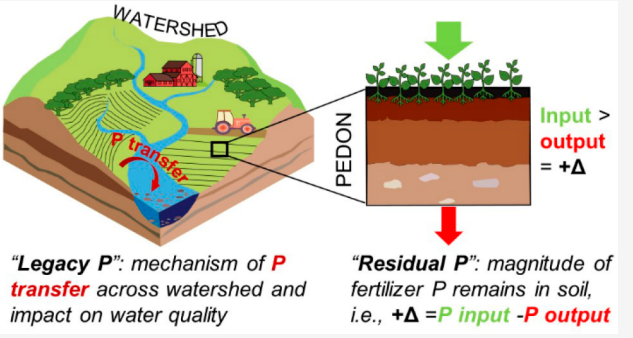
ABSTRACT: Phosphorus (P) inputs to the biosphere have quadrupled in less than a century due to intensification of rock phosphate mining and the use of P fertilizers for crop production. Accumulation of P in soils can increase P transfers across the soil-water continuum that impair aquatic ecosystem function and water resource quality for society. However, what this accumulated P is called, and subsequent connotations of magnitude versus mechanism at pedon versus watershed scale, varies in the literature. We argue that the two commonly used terms of "residual" and "legacy" P, though often used interchangeably, hold distinct meanings and connotations. Tracing the historical origins and trajectories of these terms reveals that "residual P" refers to the magnitude of fertilizer P that remains in the soil after crop harvest, whereas "legacy P" refers to the mechanism of P transfer across the watershed and its long-term impacts on water quality. The use of "legacy P" in many cases refers to the residuality of anthropogenic P inputs, and thus should be "residual P". We recommend that the term "residual P" be used when referring to the accumulation of P in soils under agricultural management from past inputs, and the term "legacy P" be used when referring to the transfer of P within watersheds. The intentional and thus consistent use of residual versus legacy P stands to provide important nuance in the environmental sciences and overlapping fields of agronomy and biogeochemistry.



KEYWORDS: *residual phosphorus, legacy phosphorus, terminology, origin and connotation, mass balance, phosphorus transfer, terrestrial-aquatic continuum*

OVERVIEW

Phosphorus (P) enrichment in the biosphere to increase crop productivity has entailed negative impacts on water resources.[1] The etiology of the "wicked problem" of P losses[2] is in large part the unused anthropogenic P added to soils as an input to agroecosystems, which largely remains in the soil and accumulates over time. Although this legacy of past fertilization can and is used by future crops, the accrued P is susceptible to "leakage", exiting the agroecosystem. While agronomically minor, such P losses (e.g., < 2 kg ha^{-1} y^{-1}) have disproportionate and negative impacts on water quality via eutrophication.[3,4]

This P legacy from past management has been described by varying terms used in different ways. In agronomy and soil science, it is historically referred to as "residual P", describing a pool or magnitude of P accumulated in soils from past inputs. In the late 20th century, much research focused on capitalizing on this unused P fertilizer for crop production,[5] as reflected by the terms "residual value"[6] or "fertilizer residues".[5] In the past decade, the *notion* of utilizing historically accumulated P has returned in vogue—though often phrased as mining or accessing or utilizing "legacy P".[7] Yet, "legacy P" also arises in the literature on P in catchments and watersheds,[8,9] where it at times appears to share the anthropogenic connotations of the agronomic and soil science usage (e.g., buildup of fertilizer P in surface soils),[10] but in other cases appears wholly distinct, such as an amount of P transferred from agricultural fields to streams.[11]

The question then is, legacy *of what*? Legacy of the past fertilizer P or legacy of the P transfer process? To answer this question, an overview of the connotations and origins of "residual" versus "legacy" P is warranted.

ORIGINS AND HISTORY OF RESIDUAL P

Anthropogenic P retained in soils from past inputs or stored in catchments from historical deposition is generally known as *residual P*.[4,12,13] However, the specific definition of residual P is not always clear and varies among contexts and disciplines (Table 1).[14,15] Residual P and legacy P are often used interchangeably in the same study (Table 1).[16−18] In these cases, the reason for why which term was used seems ambiguous and appears largely dependent on personal preference. The

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Table 1. Summary of the Uses of "Residual P" or "Legacy P" or Both and the Given Definitions by Different Fields of Studies

Term	Definition	Field of study	Reference
Residual P	"Residual phosphorus left in the fertilized area after the corn plant had grown to maturity"	Agronomy	Harper[19]
Residual P	"The application of phosphorus (P) as either fertilizers or manures in excess of plant requirements causes a buildup of P in the soil"	Agronomy	McDowell and Sharply[14]
Legacy P	"Legacy soil P is defined here as the cumulative P that has been added to soils in fertilizers and manures since they were first cultivated, minus P removed in harvested crops and in run-off through erosion and leaching"	Agronomy	Rowe, Withers, Baas, Chan, Doody, Holiman, Jacobs, Li, MacDonald, McDowell, Sharpley, Shen, Taheri, Wallenstein, and Weintraub[13]
Legacy P	"Accumulated legacy P from historical land management can serve as a P source to aquatic environments via surface and subsurface pathways over decades or longer, often with a detrimental effect on water quality"	Agronomy	Liu, Hu, Yang, Abdi, and Cade-Menun[30]
Legacy P	"The buildup of soil P beyond plant requirements can lead to a long-term legacy of P losses that could impair surface water quality"	Agronomy	McDowell, Dodd, Pletnyakov, and Noble[31]
Legacy P	"Historically, fertilizer P has been applied in excess of crop demand resulting in an accumulation in soil P over time"	Soil science	Teng, Zhu, Shao, Zhang, Li, and Whelan[28]
Legacy P	"Accumulated P can be remobilized or recycled, acting as a continuing source to downstream water bodies for years, decades, or even centuries"	Environmental science	Sharpley, Jarvie, Buda, May, Spears, and Kleinman[4]
Legacy P	"Legacy effect, associated with the buildup of P in the topsoil, and the complex release patterns in catchments and their rivers"	Environmental science	Haygarth, Jarvie, Powers, Sharpley, Elser, Shen, Peterson, Chan, Howden, Burt, Worrall, Zhang, and Liu[10]
Legacy P	"The term legacy P refers to P accumulated within the land-freshwater continuum that can serve as long-term P source to surface water"	Environmental science	Jiang and Yuan[32]
Legacy P	"Anthropogenic P that accumulates in the watershed overtime, known as legacy P, is a form of storage, but can also act as a chronic, diffuse source of P to downstream waters, even when new inputs are stopped"	Environmental science	Goyette, Bennett, and Maranger[9]
Legacy P	"The remainder of human input P (fertilizer/manure) accumulates in agricultural soils, groundwater, lakes, and rivers along the land-to-sea of nutrient"	Environmental science	McCrackin, Muller-Karulis, Gustafsson, Howarth, Humborg, Svanbäck, and Swaney[15]
Legacy P	"Legacy P is an important component of the P transferred from fields to receiving waters and contributes so slowing the recovery of eutrophic systems"	Hydrology	Lannergård, Agstam-Norlin, Huser, Sandström, Rakovic, and Futter[11]
Residual or legacy P	"P applied to agroecosystems in the form of mineral fertilizers, manures, and wastes is retained in the soil as inorganic and organic P that is otherwise only sparingly available to plants"	Environmental science	Condron, Spears, Haygarth, Turner, and Richardson[12]
Residual or legacy P	"The accumulation of residual or legacy P-the fraction of P inputs that binds to agricultural soils and is neither lost to runoff nor taken up by plants in the short term-can have important, long-term consequences for receiving water bodies"	Agronomy	Wironen, Bennett, and Erickson[17]
Residual or legacy P	"Disproportionate fertilizer and manure P use in industrialized countries led to low P-use efficiency (PUE). Consequently, over time large amount of surplus P were retained as residual P in soils"	Agronomy	Langhans, Beusen, Mogollón, and Bouwman[16]
Legacy or residual P	"Even after the reduction or cessation of fertilizer inputs, the large surplus of P accumulated in soil (known as legacy P, or residual P) can continue to pollute surface waters, offsetting or delaying benefits brought by nutrient-abatement measures"	Agronomy	Zou, T., Zhang, X., Davidson, E.A.[18]
Legacy or residual P	"The large reservoirs of residual P accumulated over decades of cultivation, namely legacy P"	Agronomy	Pavinato, Cherubin, Soltangheisi, Rocha, Chadwick, and Jones[33]

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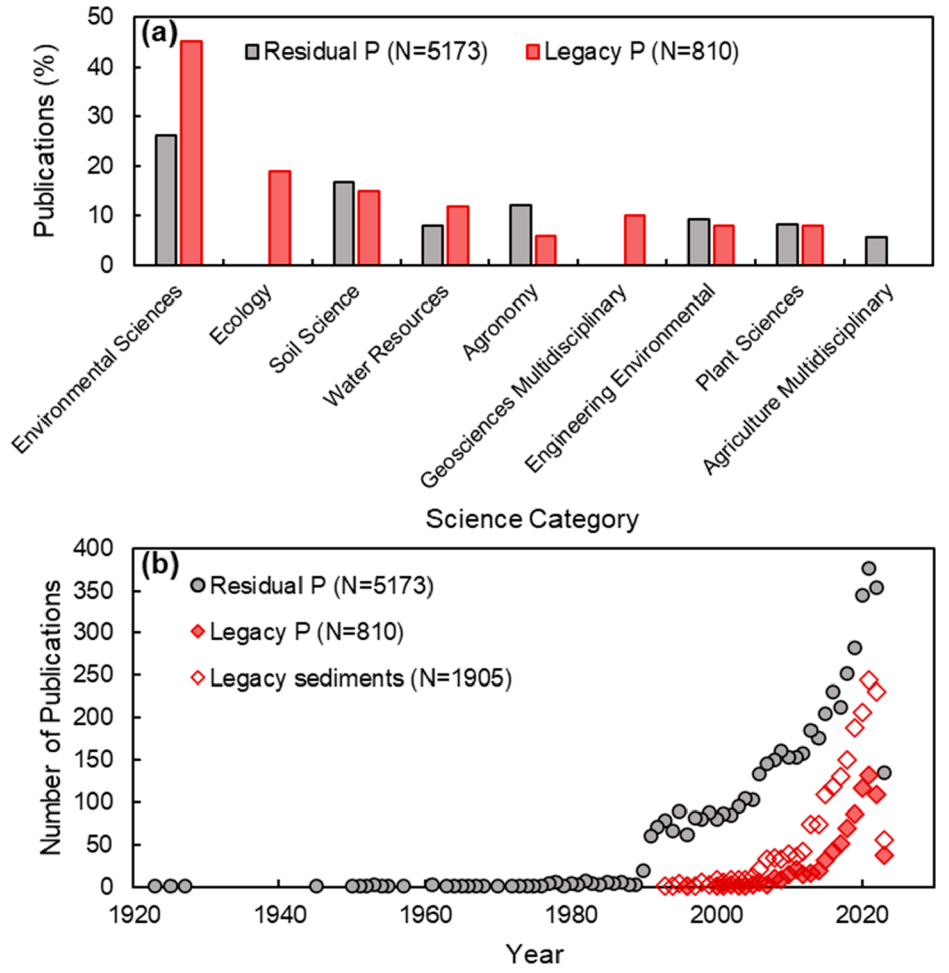

Figure 1. (a) Percentage of publications by top nine fields of study and (b) number of publications by publishing year yielded by searching "residual phosphorus", "legacy phosphorus", and "legacy sediments", in the Web of Science Core Collection database (June 14, 2023). *N* is the total number of publications yielded by each search.

interchangeable[12,17,18] or arbitrary uses of these two terms can cause ambiguity in the scientific community. A survey of peer-reviewed articles that contain the two phrases indicates that the use of term "residual P" has been mainly in environmental sciences, soil science and agronomy, whereas "legacy P" is used in environmental sciences and soil science but more broadly across ecology, water resources science and geosciences (Figure 1a).

The earliest occurrence of the term "residual P" dates back to 1925, in an investigation of the secondary effect of in-row fertilization in Iowa as compared to broadcast fertilization on crop yields.[19] Here, residual P refers to the fertilizer P "left in the fertilized area after the corn has grown to maturity" (Table 1). Residual P increased exponentially in use post-1990 (Figure 1b) in studies on P surplus in soils under agricultural use due to fertilizer overapplication or low crop P use efficiency.[20] In some instances, residual P was specifically evaluated as a means to front-load P applications for multiple cropping years, as opposed to annual applications.[21] In other cases, the focus was on evaluating the accumulation and decline of P in soil as a function of intentionally applying more or less P than what was removed by the crop.[22] These studies established that same-season application generally entails higher crop use efficiency of P inputs than a single higher dose meant to last for multiple cropping seasons. Thus, the interest in residual P seems to have shifted over time from an intentional agronomic strategy to one of posthoc capitalization on the legacy of positive P balances.

■ ORIGINS AND HISTORY OF LEGACY P

The term "legacy P" did not appear in published articles until 1996, 71 years after the first use of the term residual P, when hydrologists Kadlec and Knight observed a net positive P balance in a wetland in Florida and proposed that "the wetlands might have been expected to be discharging accumulated legacy phosphorus from prior use".[23] A series of reports on water quality in Florida in 2006−2008 used the term to refer to past accrued P, anthropogenic or not, that has contemporary impacts on water quality.[24] Since 2008, the use frequency of legacy P in publications has increased exponentially (Figure 1b). In most cases, legacy P is used to refer to an accumulated P surplus in agriculturally managed soils that serves as a long-term P source to aquatic environments via surface or subsurface loss pathways.[9,11,15] In other cases, legacy P is used to describe "stores" of P that have "accumulated in watersheds and water bodies"—a nod to the positive mass balance definition of residual P in the original agricultural context but focused on water quality implications.[25] The use of legacy P appeared and grew contemporaneously with the use of "legacy sediment" in the early 2000s (Figure 1b), which in environmental sciences refers to anthropogenic terrestrial sedimentary deposits.[26]

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Increasing use of the broadly defined "legacy P" likely reflects the needs of rapidly growing interdisciplinary research (e.g., environmental sciences) and emerging or accelerating environmental challenges (e.g., eutrophication) in the Anthropocene.

WHY TERMINOLOGY MATTERS

Usage of the terms residual P and legacy P has proceeded without explicit definitions and relies on preconceived understandings or implications that may vary among disciplines. The primarily implied meanings are the anthropogenic origin *or* the age of the P—and the problem is that these meanings sometimes but not always overlap. Here, the etymology of residual and legacy is instructive. "Residual" is defined by the Merriam-Webster Dictionary as "the difference between results obtained by observation and by computation from a formula or between the mean of several observations and any one of them" whereas "legacy" is "something transmitted by or received from an ancestor or predecessor or from the past". In other words, residual P simply refers to a positive mass balance calculated for the agricultural system: residual P = P inputs via fertilizers or manures − P removed by crop harvest and losses. In contrast, legacy P emphasizes how the transport of P impacts water quality over time.[27]

RECOMMENDATIONS

We propose that researchers and policymakers be intentional in the use of residual versus legacy P. Given their distinct origins and connotations, the terms residual P and legacy P should not be used interchangeably. Though increasingly common, legacy P should not be used when residual P is more appropriate.[28] Residual P holds connotations that are more relevant to the terrestrial context (e.g., soil or field scale) involving a range of time scales from short (e.g., seasons) to long (e.g., decades), whereas legacy P is more suited for the terrestrial-aquatic continuum (e.g., watershed scale) with longer biogeochemical cycling time scales (e.g., decades and centuries).[29] We recommend that the term "residual P" be used when referring to the accumulation of P in soils under agricultural management from past inputs, and that the term "legacy P" be used when referring to the transfer of P within watersheds.

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Notes

The authors declare no competing financial interest.

Biographies

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Dr. Andrew J. Margenot is an Associate Professor and director of the Soils Lab at the University of Illinois Urbana−Champaign, U.S.A. He earned his B.A. in Philosophy and Biochemistry from Connecticut College in 2010, and a Ph.D. in Soils & Biogeochemistry at University of California Davis in 2016, studying nutrient cycling in tropical agroecosystems. Dr. Margenot's research team evaluates biogeochemical mechanisms that underpin agroecosystems function, with a dual emphasis on nutrient cycling and transformations that contribute to input use efficiency and water quality protection.

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