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Soil Olsen P response to different phosphorus fertilization strategies in long-term experiments in NW Italy

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Abstract

Soil available P for crops, derived from P inputs and regulated by soil chemical, physical and biological factors, represents a small fraction of the total P content. Soil P balance (P input minus P output) is potentially a good descriptor of fluctuations in the available P pool, making it possible to compare experiments that differ in management and duration. Using a data set compiled from three long-term experiments in NW Italy that tested different P fertilization types (nil, mineral, organic and manures), cropping systems and P balances in different soils, this paper focused on (a) proposing an empirical exponential model to describe the relationship between variables and (b) providing an agronomical interpretation of optimized parameter values, to set the basis for a unified interpretation of long-term dynamics of soil plant-available P. The pooled data fit well in an exponential model that identified three factors supportive of an agronomic interpretation, two linked to soil attributes and one that differentiated fertilizer types. Soil characteristics were found to affect minimum soil Olsen P values in depletion and response rates with additions, while fertilizer type had a multiplier effect on cumulative P balance. Farmyard manure was shown to build the available P pool better than other organic sources (bovine slurry, commercial organic fertilizers, green manure) and inorganic fertilizers, owing to a high C/P. The exponential model provided a good theoretical basis, but further studies are needed to correlate parameter values to soil (e.g., carbonates, Al and Fe oxide content) and fertilizer (e.g., C:P, lignin:P) characteristics and to verify the model applicability to different conditions.

KEYWORDS

cumulative P balance, exponential model, long-term experiments, P availability, P source

1 | INTRODUCTION

Phosphorus (P), an essential nutrient for plant growth, is absorbed from the soil solution primarily in the form of orthophosphate ion (Jalali, 2009; Zhu et al., 2018). Even at high levels of soil total P, only a small fraction (<1%) of total P is actually available for crop uptake (Ohm et al., 2017; Zhu et al., 2018; Zicker et al., 2018). Soil chemical, physical and biological factors (Blake et al., 2000; Eichler-Löbermann et al., 2007) regulate available P in

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a variety of ways. Chemical factors that most influence available P include soil mineralogy, pH, organic matter, adsorption capacity and the presence of other chemicals (Aulakh et al., 2007; Hinsinger, 2001). In the case of pH, P deficiency can occur in either acidic or alkaline conditions because of P adsorption on Fe and Al oxides or P precipitation as Ca phosphates, respectively (Sharpley, 1995). Among the physical factors of soil that affect P availability, texture, temperature, aeration and soil moisture all play fundamental roles (Reijneveld et al., 2010; Schröder et al., 2015). Biological factors that most influence available P are root presence, crop residues, and bacteria and fungi (Ciampitti et al., 2011; Zhu et al., 2018). Each plant species has a different capacity to extract P from the soil through root exudation of organic acids, ions and phosphatases (Hinsinger, 2001). The amount of fertilizer certainly influences the amount of P that crops can utilize, but several authors, such as Edmeades (2003) and Shen et al. (2014), showed that available P also varies with the source of supplied P (e.g., organic or inorganic fertilizers).

The sustainable use of phosphate-based fertilizers is a priority to make the agricultural system more environmentally sustainable (Tian et al., 2020) and promote the use of farm manures under correct agronomic principles (Bassanino et al., 2011). The implementation of fertilizer best management practices (4Rs: right nutrient source, right rate, right time and right place) aims to achieve the soil available P concentration able to enhance plant growth and to allow production goals of the farm (Roberts & Johnston, 2015; Simpson et al., 2011). Fertilizer-recommendation methods, either as Decision Support Tools or simple guidelines, require an estimate of the amount of P released from the soil (Jordan-Meille et al., 2012; Reijneveld et al., 2010). There is no doubt that the best method to measure the plant-available P is to analyse the plant itself; there is in fact no agreement on which chemical extraction best mimics the root behaviour (Dyson & Conyers, 2013; Nawara et al., 2017). The most commonly employed methods to measure soil available P (Olsen, Mehlich-3 and Bray-1) correspond to a specific extractor type and pH value, and their reliability depends on the soil type (Reijneveld et al., 2010). The Olsen method (Olsen et al., 1954) is used for soils with mildly acid, neutral or alkaline pH, and it has wide international acceptance as an indicator of soil P fertility (Bierman & Rosen, 1994; Ma et al., 2009; Pagliari et al., 2010). Conversely, the Mehlich-3 method was developed for soils with acid to neutral pH (Zhang et al., 2014) and the Bray-1 method is indicated for soils with pH below 6.8 (Bray & Kurtz, 1945). The Olsen method is the reference standard in Italy. However, as Withers et al. (2007) reported, Olsen P averages only 2,7% of the total P in the 24 European soils that have been deeply characterized, which makes clear the importance of available soil P compared with measures of total soil P. Consequently, different estimation methods of soil available P may lead to very different recommendations of crop fertilizer requirements.

Common practice shows farmers often apply excess mineral P fertilizers because of the fear of low soil P availability, high-fixing soil capacities and low use efficiencies of mineral fertilizers (*c*. 20%) (Ciampitti et al., 2011; Roberts & Johnston, 2015; Zhu et al., 2018). P supply using organic fertilizers also exceeds crop requirements (Borda et al., 2011), because manure and slurry application guidelines are based on nitrogen, and the organic fertilizer N/P ratio is generally lower than that of plants. Then, because of the oversupply, soil P tends to accumulate over the long term (Alamgir et al., 2012; Ciampitti et al., 2011; Withers et al., 2001) and cause agricultural pollution through run-off and leaching (Lemercier et al., 2008; Messiga et al., 2010; Sharpley, 1995). Unfortunately, the amount of fertilizer to be supplied to crops is not explicitly ruled in any European-wide regulation; however, several European countries or regions have come to suggest specific limitations based on crop and/or soil characteristics to restrict P fertilization (Amery & Schoumans, 2014; Garske et al., 2020). In the Piedmont Region of northwest Italy, where this study is set, voluntary measures by the Rural Development Programme require that fertilization is withdrawn when the soil Olsen P concentration exceeds 25 mg kg^{-1} (Regione Piemonte, 2018). A pragmatic unique threshold concentration for all types of soils was set by the local legislation. Phosphorus accumulation in soils, termed legacy P, represents a large and global secondary source of P and could substitute manufactured fertilizers and improve preservation of limited phosphate rock reserves in the medium term (Rowe et al., 2016).

On the other hand, some locations may face severe P deficiency. When no fertilizer is added or when P supply < P removal, soil P availability declines, which may result in soil degradation and reduced capacity to sustain high crop yields (Ciampitti et al., 2011). Nevertheless, if the soil is rich due to past surpluses, it may take many years to reach such a significant depletion of soil available P (Sharpley, 1995).

A regional scale analysis of soils in Piedmont, NW Italy, pointed out that in the last decade, the soil Olsen P concentration increased in areas where most of the livestock farms are located, while it decreased in stockless areas, and in the paddy rice area (M. Battisti, unpublished data). Less recent data show that the fertilization management with both mineral and organic fertilizers provoked a P unbalance from −17 to 52 kg P ha^{-1} in the region (Bassanino et al., 2011). The same authors identified the highest P surplus in the lowland Piedmont Region where the stocking rate is high.

Several field-scale experiments have been conducted in the past decades to relate the plant-available soil P to fertilization practices including P accumulation, maintenance, and depletion in the long-term (Messiga et al., 2010). There is a general agreement on the need to explore variations over long periods, because of the slow reaction of soil (Morari et al., 2008; Van der Bom et al., 2017; Zicker et al., 2018), but the explanatory variable used was in some cases time (Dodd & Mallarino, 2005; Johnston et al., 2016; Ma et al., 2009; Singh et al., 2016), in some other the net amount of P supplied, that is P balance. Soil surface P balance accumulated over time, in particular, has shown a great potentiality to compare cropping systems that vary in removal capacity and time duration. Many studies have found a positive correlation between soil available P and P balance (Blake et al., 2000; Colomb et al., 2007; Shen et al., 2014; Sucunza et al., 2018; Van der Bom et al., 2017). In the literature, most of the authors have explored a limited set of soil types, starting levels of soil available P, time spans, and fertilizer types and amounts, and in most cases, a simple linear relationship well described the relationship between P balance and plant-available soil P (Ciampitti et al., 2011; Messiga et al., 2010; Paris et al., 2004). The hypothesis that underlies a non-linear model is that processes that govern the available fraction of soil P are capable of two opposite responses, exerting a buffering effect at low availability rates, and a more than proportional increase, above a threshold for the soil capacity to hold them is reached (Ter Meulen, 1993). However, there is still a lack of consensus on which mathematical model should be used when a wider variability of P balance is explored and the linear model shows limited accordance with data. The model should be flexible, robust and possibly provide an interpretation of data that will allow an independent prediction of parameter values.

With this aim in mind, the research described here relied on three databases acquired from three long-term experiments that differed in soil characteristics, P fertilization type, cropping system, and P balance that were compared using the P balance accumulated over time. Using this data set, we intended to answer the following research questions:

- Can P accumulated balance predict soil Olsen P in the studied situations, spanning different cropping systems and soils, and a wide range of fertilization types and amounts, using a unique empirical model?
- Will the empirical model support an agronomical interpretation of optimized parameter values?

FIGURE 1 The location of the three long-term experiments in the Piedmont Region (NW Italy)

TABLE 1 Properties of the topsoil (0–30 cm) at the start of the LTE sites

	Lombriasco	Cussanio	Tetto Frati
Sand (%)	52.1	42.4	48.2
Silt (%)	35.3	47.5	44.3
Clay (%)	12.6	10.1	7.5
Soil pH_{H2O}[a]	6.5	6.5	8.1
$CaCO_3$ (%)[b]	0.0	0.0	4.7
Organic C (%)[c]	0.980	1.053	0.970
CEC ($cmol_{(+)}$ kg^{-1})[d]	9.0	11.0	10.1
Total N (%)[c]	0.109	0.107	0.126
Exchangeable K (mg kg^{-1})	29.3	39.4	14.4
Bulk density (g cm^{-3})	1.61	1.59	1.42

[a] pH 1:2.5 *w/v* H_2O

[b] volumetric calcimeter method (Loeppert & Suarez, 1996).

[c] CHN elemental analyser (Flash EA 1112, Thermoquest; MIPAF, 2000).

[d] $BaCl_2$ extraction (Sumner & Miller, 1996).

[e] $BaCl_2$ extraction followed by AAS determination (Sumner & Miller, 1996).

2 | MATERIALS AND METHODS

2.1 | Experimental sites

This study analysed data from three long-term experiments (LTEs) (Lombriasco, Cussanio and Tetto Frati) located in the Po River plain of the Piemonte Region in northwest Italy. Situated about 50 km apart (Figure 1), all locations experience sub-continental climate conditions with mean annual temperatures between 11.8 and 12.9°C and total annual rainfalls between 702 and 760 mm. Table 1 indicates the main chemical characteristics of the soil at initiation of the LTEs. The two soils at Lombriasco and Cussanio appear rather similar, while Tetto Frati has a deep calcareous and coarser-textured soil with low initial available P content. The soil organic matter (SOM) content was medium at all sites. Different treatments were considered at each site, whose details are reported in Table 2.

TABLE 2 Treatments included in the study and details of the amounts of P supplied. Each treatment name is composed of 2–3 sections, separated by a hyphen. The first section includes an uppercase letter for the name of the site (L, C or T for Lombrisco, Cussanio and Tetto Frati), and a lowercase letter to indicate the time span (l, m or s for long, medium or short-term). The second section indicates the type of fertilizer, as detailed here. The third section, where present, indicates the starting soil P level (Lo for low and Hi for high) in some of the treatments

site	Time span	Fertilization strategy and kg ha^{-1} $year^{-1}$ of P supplied	Initial soil Olsen P (mg kg^{-1})	Treatments
Lombriasco (L)	1996–2016 (l)	Nil	49.0	Ll−0
Lombriasco (L)	2007–2016 (m)	Nil	50.3 (Hi)	Lm−0-Hi
Lombriasco (L)	2007–2016 (m)	Nil	27.8 (Lo)	Lm−0-Lo
Lombriasco (L)	1996–2007 (m)	Mineral, 35	60.2	Lm-Min
Lombriasco (L)	2007–2016 (m)	Compost/digestate, 30	47.6 (Hi)	Lm-Org-Hi
Lombriasco (L)	2007–2016 (m)	Compost/digestate, 30	26.9 (Lo)	Lm-Org-Lo
Cussanio (C)	2000–2012 (m)	Nil	28.8	Cm−0
Cussanio (C)	2006–2012 (s)	Nil	37.5	Cs−0-Hi
Cussanio (C)	2006–2012 (s)	Nil	29.0	Cs−0-Lo
Cussanio (C)	2000–2012 (m)	Farmyard manure, 42	38.3	Cm-Fym
Cussanio (C)	2000–2012 (m)	Organic fertilizers, 39 + Green manure	18.7	Cm-OG
Cussanio (C)	2006–2012 (s)	Farmyard manure, 39	38.3	Cs-Fym
Cussanio (C)	2006–2012 (s)	Organic fertilizers, 32 + Green manure	34.7	Cs-OG
Tetto Frati (T)	1992–2012 (l)	Mineral, 60	*n*.d.	Tl-Min
Tetto Frati (T)	1992–2012 (l)	Bovine slurry, 25 and 51, + Mineral, 29	*n*.d.	Tl-Slu
Tetto Frati (T)	1992–2012 (l)	Farmyard manure, 46 and 90, + Mineral, 29	*n*.d.	Tl-Fym

2.2 | Lombriasco

The Lombriasco site, located at 44°50′N, 7°38′E, contains soil classified as Typic Hapludalf, loamy sand, coarse-loamy, mixed, non-acid, mesic (Soil Surface Staff, 2014). The LTE had been managed as a grain commercial farm with winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), soya bean (*Glycine max* (L.) Merr.), and maize cultivated under a 4-year crop rotation. All wheat cultivars were classified as hard (Cocchi et al., 2005), while all maize hybrids were in the FAO maturity group 500; soya bean varieties belonged to maturity group 1+. Each year, the wheat straw was removed and maize and soya bean residues were incorporated into the soil. Over the years, comparisons were made of three different treatments: tillage (ploughed vs. minimum tillage), fertilizer type (organic vs. mineral) and NPK total supply. This LTE was started in 1996 with large plots. At the end of this phase, each large plot had a different soil P content that was set as the initial value for a second experimental phase of the platform. To consider new treatment sets and various fertilization strategies to soils of varied initial P content, the design was in fact modified in 2007 to a split-plot design with four replicates. Mineral fertilizers were used before the LTE started. For further details, see Alluvione et al. (2011) and Moretti et al. (2020).

Three fertilization strategies were considered at the site: no P supply, moderate P mineral fertilization, and organic P fertilization using compost. The effect of no P supply was tested during two periods:

1. long-term period of 20 years (Ll-0);
2. medium-term period of 9 years on plots with two different initial soil Olsen P concentrations, high (Lm-0-Hi) and relatively low (Lm-0-Lo).

The effect of adding P supply was tested in the following circumstances:

1. medium-term period of 11 years on plots where mineral fertilizers were supplied as triple superphosphate (Lm-Min);
2. medium-term period of 9 years on plots at two initial soil Olsen P concentrations (Lm-Org-Hi and Lm-Org-Lo), both fertilized with composted municipal solid waste (MSW compost) or digestate.

2.3 | Cussanio

The Cussanio site (44°34′N, 7°41′E) contained soil classified as Aquic Haplustept, coarse-loamy over loamy-skeletal, mixed, non-acid, mesic (Soil Surface Staff, 2014). The three-replicate experimental design was set in 2000 as big plots and then modified in 2006 into split plots and a different crop rotation. Like at Lombriasco, the splitting of the original big plots in the second phase gave rise to a set of treatments applied to differentiated initial soil P levels. The original 3-year rotation of winter wheat – soya bean or field pea (*Pisum sativum* L.) – maize was also revised into a 4-year crop rotation of wheat and maize with 2 years of grass meadow. Maize and pulse varieties were similar to those used at Lombriasco, while wheat cultivars were of the soft class (Cocchi et al., 2005). The wheat straw was removed, while residues of maize and pulses were incorporated into the soil. Prior to the start of the experiment, mineral fertilizers were used only in a cereal production system. Further details are reported in Sacco et al. (2015).

This experiment allowed us to study the absence of P supply under two situations:

1. medium-term period of 12 years (Cm-0);
2. short-term period of 6 years on plots with two different initial soil Olsen P concentrations (Cs-0-Hi and Cs-0-Lo).

The P supply was tested under two scenarios:

1. medium-term period of 12 years on plots fertilized with as farmyard manure (Cm-Fym) and on plots supplied with commercial organic fertilizers authorized for organic farming. This treatment also included a vetch (*Vicia villosa* L.) green manure (Cm-OG);
2. short-term period of 6 years on plots supplied with farmyard manure (Cs-Fym) and on plots fertilized with organic fertilizers, including vetch green manure (Cs-OG).

2.4 | Tetto Frati

The Tetto Frati site was located at 44°53′N, 7°41′E, where the soil is classified as Typic Udifluvent, coarse-loamy, mixed, mesic, calcareous (Soil Surface Staff, 2014). This LTE was established in 1992. The experimental design (randomized block with three replicates) compared four cropping systems: maize for silage, maize for grain with straw incorporation, silage maize + Italian ryegrass (*Lolium multiflorum Lam.)* double cropping and 4-year or 6-year rotation of silage maize and grass ley with three fertilizer management strategies described here:

1. constant mineral P application level as triple superphosphate (**Tl-Min**);
2. two rates of bovine slurry corresponding to 170 and 340 kg N ha^{-1}, where the amounts of applied P varied correspondingly, plus a mineral P contribution (**Tl-Slu**);
3. two rates of farmyard manure plus triple superphosphate, again based on fixed N dosed from manures (**Tl-Fym**).

Each of the considered fertilization managements spanned 20 years (1992–2012), details of which are reported in Zavattaro et al. (2016). All maize hybrids were chosen in the FAO maturity group 500.

2.5 | P balance

The annual P soil surface balance was calculated as the difference between total P supply and P removal following the IRENA (Indicator Reporting on the Integration of Environmental Concerns into Agriculture Policy) method (EEA, 2006). Various P supply sources included mineral and organic fertilizers, farmyard manure, slurry or compost, while P in seeds and atmospheric deposits was considered as negligible (Messiga et al., 2010). Removals of P from the system included P contained in the harvested yield and in crop residues – if removed from the field. These values were calculated from dry matter yields and their P contents, assessed every year for all crops and added matrices.

Accumulated P balance was calculated as the sum of annual P balances for the period between experiment start and soil sampling for Olsen P determination.

The C:P ratio of supply sources was calculated by averaging available data of their compositions (not all years were available), weighted over the amounts distributed in OG treatments, where different sources were used.

2.6 | Soil sampling

The soils were sampled periodically from the three sites to determine Olsen P. At Lombriasco, where experimental plots were 300 m^2 wide, sampling occurred every 3 years (i.e., six times in the 20-year long-term treatment and four times in the 9-year medium-term treatments). At Cussanio, where experimental plots were 300 m^2 wide, sampling occurred five times in the 12-year medium-term treatments and three times in the 6-year short-term treatments. Only in Tetto Frati (75-m^2 wide plots) did sampling occur just once; it was performed in 2012 after a 20-year long-term period.

The sampling procedure was identical at each site in that three soil cores were taken from the first layer (0–30 cm) of each different treatment plot using a 7 cm diameter auger, and mixed to obtain a final sample of *c*. 1.5 kg. All soils were air-dried and sieved through a 2-mm mesh screen. Plant-available P was determined using the Olsen method (Olsen et al., 1954).

To allow for a more generalizable relationship between variables, soil Olsen P concentration (mg kg^{-1}) was used in place of soil P content (kg ha^{-1}), which depends on soil bulk density.

2.7 | Data analysis

The relationship between soil Olsen P and cumulative P balance was described on pooled treatments and sites using the exponential model (1):

$$OlsenP = a + b * e^{(c*PB)}, \tag{1}$$

where *PB* is the accumulated P balance observed in each treatment when Olsen P was measured, and a*a*, *b* and *c* are fitting coefficients. Parameters *a* and *c* were set as specific for each soil. Parameter b was split into two additive components, one valid for all soils (b_0 parameter), and five components, specific for each of the types of supply used the experiments (b_{Min}, b_{Org}, b_{OG}, b_{Fym} and b_{Slu}). The initial soil P status was not included among explanatory factors because it was considered just a transient condition, originated by the past history and not a descriptor of each observed treatment.

A matrix was built using all accumulated P balance and soil Olsen P data, setting dummy variables to include/not to include specific additive effects to the three parameters. A dummy variable is a binary variable that can take the value of 0 or 1. Three dummy variables described the type of soil for *a* and *c* parameters. Six dummy variables indicated five different types of P supply and one reference for unfertilized treatments. The following equation then represents the statistical model:

$$\begin{gathered} OlsenP = \left(L*a_L + C*a_C + T*a_T\right) + \\ \left(b_0 + Min*b_{Min} + Org*b_{Org} + OG*b_{OG} + Fym*b_{Fym} + Slu*b_{Slu}\right) \\ *\,e^{\left(\left(L*c_L + C*c_C + T*c_T\right)*PB\right)}, \end{gathered} \tag{2}$$

where parameters *a*, *b* and *c* were defined above and are detailed in Table 3, while *Min*, *Org*, *OG*, *Fym* and *Slu* are the amounts of P supplied in each treatment under a defined strategy, and *PB* is the accumulated P balance at the time *OlsenP* was measured. The field replicates were kept separated.

The fitting procedure used the nls function in the R software (R Core Team, 2019) statistical package.

3 | RESULTS

3.1 | Soil Olsen P response to zero P supply

Soil Olsen P responded to a negative cumulative P balance. In the absence of additions to the soil of P mineral and organic fertilizers, the negative net balance led to a progressively larger accumulated negative balance (deficit) that varied with the amount of annual P removed and experimental duration (Figure 2). The Ll-0 long-term treatment showed the largest negative P balance among the treatments considered (−581 kg P ha^{-1}, on average) after 20 years of observation, which was followed by Cm-0 (−292 kg P ha^{-1}, on average) after 12 years. The 9-year, medium-term treatments, Lm-0-Hi and Lm-0-Lo, exhibited P balances of about −245 kg P ha^{-1}. Treatments that went without a supply of P, which also had the shortest periods (6 years), yielded the least negative P values: Cs-0-Hi (−149 kg P ha^{-1}) and Cs-0-Lo (−162 kg P ha^{-1}).

The different cumulative negative balances caused variable effects on the dynamics of soil Olsen P. In one group of treatments, soil Olsen P fell as the cumulative P deficit grew. The resulting reductions for this group from the initial values were 17.3 mg kg^{-1}, 7.5 mg kg^{-1} and 6.0 mg kg^{-1} in Ll-0, Lm-0-Lo and Cs-0-Lo, respectively (Figure 2). A second group of treatments, including Lm-0-Hi and Cs-0-Hi, maintained soil Olsen P values in line with those from the beginning of the experiment. The Olsen P value was preserved despite their P balance deficits reached −256 kg P ha^{-1} (Lm-0-Hi) and −149 kg P ha^{-1} (Cs-0-Hi). The third treatment group, which contained Cm-0 only, produced an apparent two-step pattern;

TABLE 3 List of factors and parameters included in the model. The explanation of treatment names is reported in Table 2

Factor	Factor types	Parameter	Treatments
Soil	Lombriasco	a_L ;c_L	Ll–0; Lm–0-Hi; Lm–0-Lo; Lm-Min; Lm-Org-Hi; Lm-Org-Lo
	Cussanio	a_C ;c_C	Cm–0; Cs–0-Hi; Cs–0-Lo; Cm-OG; Cs-OG; Cm-Fym; Cs-Fym
	Tetto Frati	a_T ;c_T	Tl-Min; Tl-Fym; Tl-Slu
Fertilizer type	Absence of P fertilization	b_0	Ll–0; Lm–0-Hi; Lm–0-Lo; Cm–0; Cs–0-Hi; Cs–0-Lo
	Mineral fertilizers	b_{Min}	Lm-Min Tl-Min
	Organic fertilizers	b_{Org}	Lm-Org-Hi; Lm-Org-Lo
	Organic fertilizers + Green manure	b_{OG}	Cm-OG; Cs-OG
	Farmyard manure	b_{Fym}	Cm-Fym; Cs-Fym Tl-Fym
	Bovine slurry	b_{Slu}	Tl-Slu

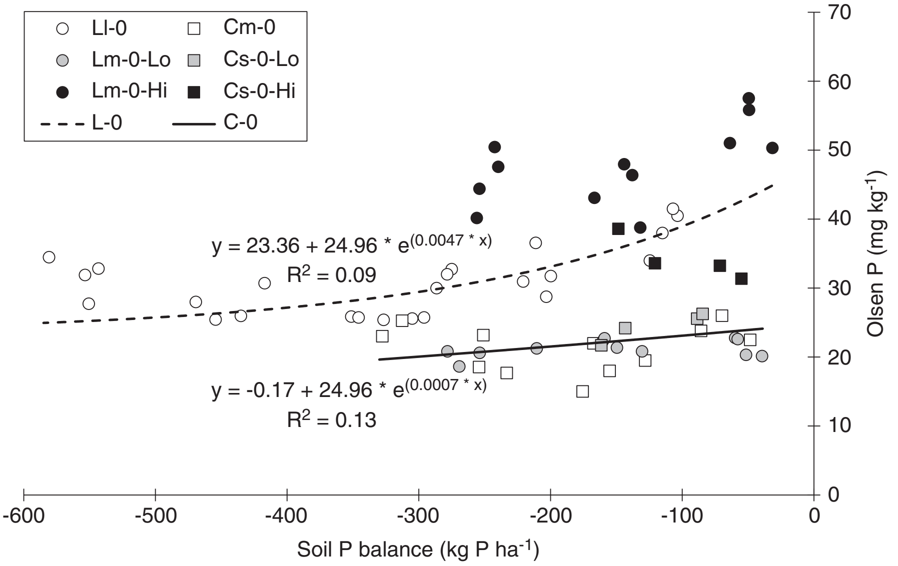

FIGURE 2 Relationship between soil Olsen P and accumulated P balance in the absence of P supply at Lombriasco in the long term (Ll-0) and in the medium term at high and low initial soil P availability (Lm-0-Hi and Lm-0-Lo, respectively); and at Cussanio in the medium term (Cm-0) and in the short term at high and low initial P availability (Cs-0-Hi and Cs-0-Lo, respectively). The interpolation lines used the parameters of equation 2 as reported in Table 4

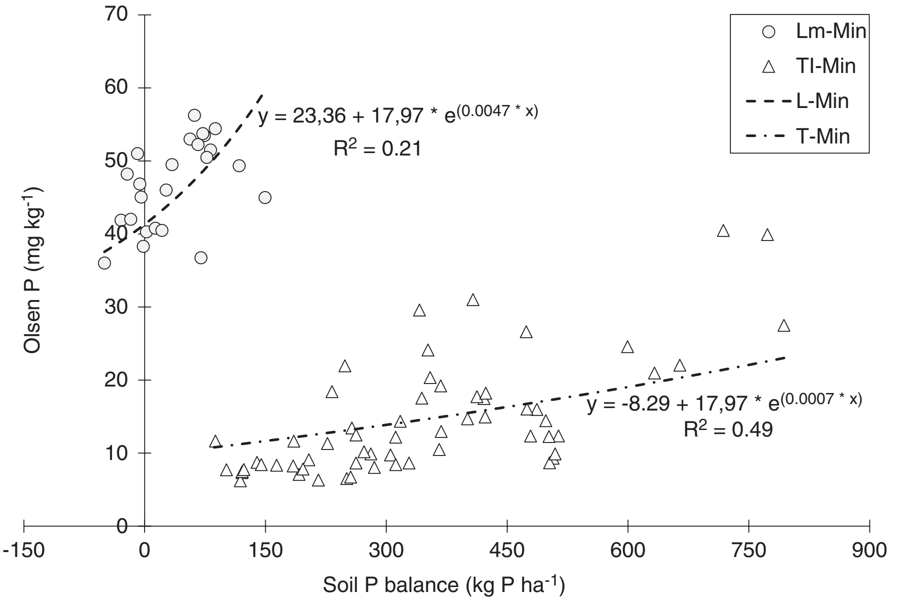

FIGURE 3 Relationship between soil Olsen P and soil P balance following repeated P supply using mineral fertilizers at Lombriasco (Lm-Min), and at Tetto Frati (Tl-Min). The interpolation lines used the parameters of equation 2 as reported in Table 4

the soil available P initially reduced and then increased to a limited extent as the cumulative deficit rose.

Typical asymptotic minimum values were detected at Lombriasco and Tetto Frati soils. The minimum at Lombriasco in Ll-0 was observed at 30 mg kg^{-1} of soil Olsen P after an initial cumulative P balance of −200 kg P ha^{-1}, and Lm-0-Lo stabilized at 20 mg kg^{-1} at −278 kg P ha^{-1}. Similarly, at Cussanio, treatment Cm-0 exhibited a minimum at a rate of 20 mg kg^{-1}, or more, after a deficit of −150 kg P ha^{-1}.

3.2 | Soil Olsen P response to mineral P supply

Two treatments—one each at Lombriasco and Tetto Frati – exhibited soil Olsen P responses to positive P balance supplied through mineral fertilizers (Figure 3). The Lm-Min treatment was managed with a fertilization supply oriented to match crop removal, such that it resulted in a soil P balance surplus of only 149 kg P ha^{-1} after 9 years. Conversely, accumulated P balances for different soils in the Tl-Min treatment ranged widely (88–794 kg P ha^{-1}) after 20 years. Furthermore, while both treatments exhibited a soil P balance surplus, the two sites displayed opposite trends. At Lombriasco, soil Olsen P clearly decreased as the accumulated P balance increased, whereas at Tetto Frati, Olsen P increased most impressively when the soil P balance increased widely.

3.3 | Soil Olsen P response to manure P supply

Four treatments, two each at Tetto Frati and Cussanio, allowed the soil Olsen P response to be studied following repetitive additions of bovine solid or liquid manure (Figure 4). The Tl-Fym farmyard manure fertilization management attained a P balance surplus above 1,350 kg ha^{-1} after 20 years. On the contrary, the slurry fertilization management at Tl-Slu built a P balance that ranged from −254 kg P ha^{-1} to + 780 kg P ha^{-1} according to the cropping system considered. The resulting variation depended both on the manure application rate and on the crop rotation. For example, at Cussanio, the P balance varied between 18 kg P ha^{-1} and 192 kg P ha^{-1}.

Phosphorus balance was shown to positively influence soil Olsen P concentration, as evidenced by results obtained from both the Tl-Fym and Tl-Slu treatments. In detail, soil Olsen P reached values from 32.0 mg kg^{-1} to 103.9 mg kg^{-1} and from 17.3 mg kg to 38.0 mg kg^{-1}, depending on the cropping system, after 20 years in the Tl-Fym and the Tl-Slu treatments, respectively. The low cumulative P surplus measured at Cussanio did not yield a clear relationship between soil Olsen P and soil P cumulative balance in either Cm-Fym or Cs-Fym treatments.

3.4 | Soil Olsen P response to other organic P fertilizer supplies

Two treatments at Cussanio that differed for the duration and the initial soil Olsen P concentration showed the soil Olsen P response to annual addition of composted organic fertilizer coupled with green manure (Figure 5). The cumulative P balance produced a surplus of 380 kg P ha^{-1} in the Cm-OG treatment (medium term, 12 years long) and of 187 kg P ha^{-1} in the Cs-OG (short term, 6 years long). The soil Olsen P concentration remained constant in Cm-OG treatment (about 31 mg kg^{-1}) despite the high P balance ($p > 0{,}05$). Conversely, in the Cs-OG treatment starting from an initial concentration

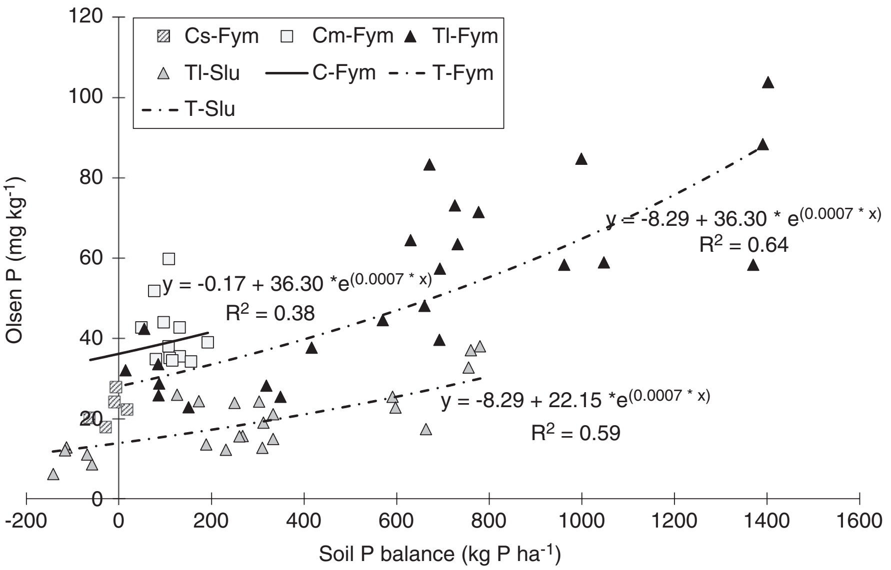

FIGURE 4 Relationship between soil Olsen P and soil P balance at Cussanio in the medium term and in the short term (Cm-Fym and Cs-Fym, respectively) following repeated additions of P supply using farmyard manure and at Tetto Frati in the long term following repeated additions of P supply using farmyard manure plus mineral fertilizers and bovine slurry plus mineral fertilizers (Tl-Fym and Tl-Slu). The interpolation lines used the parameters of equation 2 as reported in Table 4

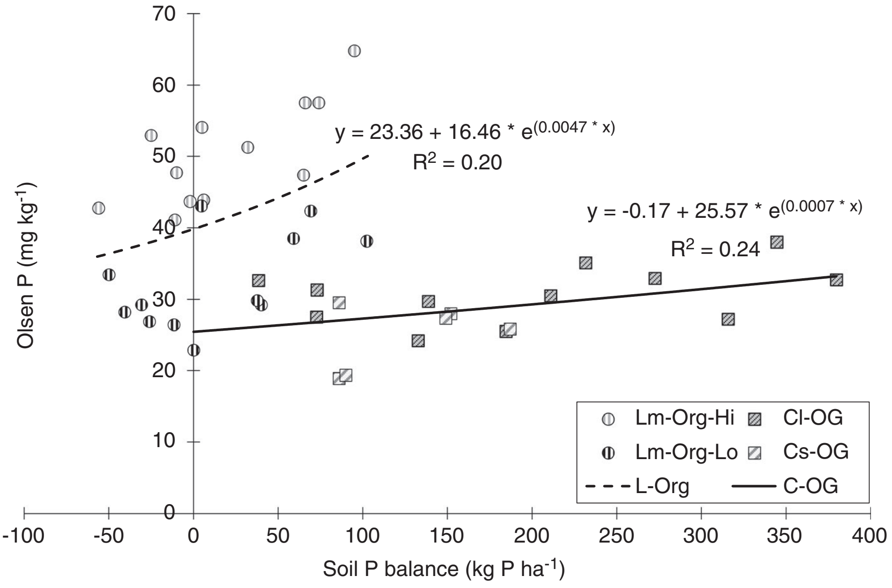

FIGURE 5 Relationship between soil Olsen P and soil P balance following repeated additions of P supply using organic fertilizers as MSW compost or digestate at Lombriasco in the medium term at high and low initial soil P availability (Lm-Org-Hi and Lm-Org-Lo, respectively) and green manure plus organic fertilizers authorized for organic farming at Cussanio in the long term and short term (Cl-OG and Cs-OG, respectively). The interpolation lines used the parameters of equation 2 as reported in Table 4

of 18.7 mg kg^{-1}, soil Olsen P increased with increasing cumulative P balance ($p < .05$).

Two treatments at Lombriasco, equal for duration but different for the initial soil Olsen P concentration, gave insight to the soil Olsen P variation to composted municipal wastes and digestate yearly addition (Figure 5). The soil cumulative P balance ranged from about –50 kg P ha^{-1} to 100 kg P ha^{-1} at both treatments.

3.5 | Exponential model of soil Olsen P response to P cumulative balance

The fitted exponential equation had a NRMSE of 9.2% ($R^2 = .74$), which was considered very good. Optimized parameter values are reported in Table 4. Parameters *a* and *c* were specific for each experimental site, while parameter *b* was common to each group of P supply types (Table 3). Parameters *b* and *c* were mathematically correlated by a logarithmic function. They were also correlated through an agronomic interpretation, as matrices and soil responses interact in strict ways to determine available soil P concentration. Parameter b changed with the characteristics of fertilization, and in particular increased non-linearly with the C:P ratio of added P sources (Figure 6).

Parameters *a* varied among the sites and were approximately 23 mg P kg^{-1} at Lombriasco and 0 mg P kg^{-1} at both Cussanio and Tetto Frati (Table 4). The *b* value was higher for farmyard manure, minimum for mineral fertilizers and organic fertilizers (MSW compost and digestate), and intermediate for bovine slurry and green manure + organic fertilizers and for the absence of P supply. The c parameter was higher at Lombriasco and not significantly different from zero at Cussanio (Table 4).

TABLE 4 Parameter values and statistics of the non-linear regression between cumulative P balance and soil Olsen P when all site and treatment data were pooled. S.E. = standard error, C.I. = confidence intervals at 2.5%–97.5%, P(t) = probability of the *t* test. For parameter *a*, statistical differences are referred to the difference between a_L, a_C, and a_T and 0. For *b* parameter, statistical differences are referred to the difference between b_{Min}, b_{Org}, b_{OG},b_{Fym},b_{Slu} and b_0. For *c* parameter, statistical differences are referred to the difference between c_L, c_C and c_T and 0

Coeff.	Estimate	*SE*	C.I.	P(t)
a_L	23.36	3.96	(15.57–31.15)	0.000
a_C	−0.17	5.02	(−10.05–9.72)	n.s.
a_T	−8.29	5.26	(−18.65–2.06)	n.s.
b_0	24.96	5.06	(14.99–34.93)	0.000
b_{Min}	−6.99	3.27	(−13.42–−0.56)	0.033
b_{Org}	−8.50	3.43	(−15.26–−1.73)	0.014
b_{OG}	0.61	4.21	(−7.68–8.89)	n.s.
b_{Fym}	11.34	3.36	(4.73–17.95)	0.001
b_{Slu}	−2.81	3.53	(−9.76–4.15)	n.s
c_L	0.0047	0.0014	(0.0019–0.0076)	0.001
c_C	0.0007	0.0005	(−0.0002–0.0016)	n.s.
c_T	0.0007	0.0001	(0.0006–0.0009)	0.000

Single R^2 values from each group of treatments ranged from 0.09 to 0.64. Although it is widely accepted that R^2 is not a good indicator of the goodness of fit in non-linear regression (e.g., Spiess & Neumeyer, 2010), it indicates a poorer model fit in depletion cases than in fertilized ones.

4 | DISCUSSION

The absence of P fertilization induced an initial drop in soil Olsen P, followed by a slow depletion until a constant level was reached. This observation agreed with reports by Ciampitti et al. (2011), in which suspension of P fertilization led to a rapid available P decrease in soils with high P levels and a gradual decline in soils with low initial P levels. Conversely, the accumulation of soil Olsen P was started slowly and grew quickly once the soil Olsen P concentration attained a critical value. Similarly, both organic and inorganic fertilizers caused soil available P to increase when applied to soils of high initial available P concentrations (Pote et al., 2003).

For medium-term scenarios, some authors found linear interpolation better for describing the effects on soil Olsen P of different fertilization managements, while an exponential one better described data pooled from different situations. A linear model means that the soil response to P fertilization is directly proportional to net additions, which may be the case under specific circumstances of soil immobilization processes. An agronomic interpretation of a linear model is quite simple – the intercept is the Olsen P value when the soil accumulated P balance is null (balanced fertilization) and at the beginning of the experiment; the slope represents the effect of each kg of P surplus or deficit on the soil Olsen P concentration.

It seems that when an experiment is limited to a single variable, a linear model is sufficient to describe the results, but when several soils and fertilization strategies (including severe depletion, heavy enrichment, and balanced fertilization) are studied, and initial soil P values are different, an exponential model function to cumulative P balance is a better descriptor of the results, both in depletion and in enrichment. Some authors used mixed models; for instance, Sucunza et al. (2018) applied a linear relationship to enrichment data and a simplified exponential model to depletion data.

The exponential model adopted here had three parameters (*a*, *c* and *b*), of which the former two were specific to soil type and the latter to P source. It had the advantage of

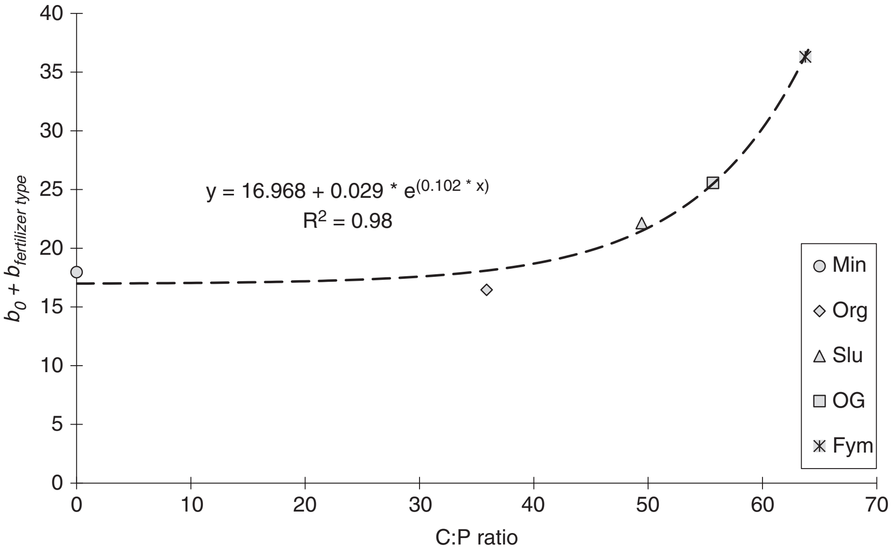

FIGURE 6 Relationship between the C:P ratio of different P sources and coefficient *b* of equation 2, calculated as $b_0 + b_x$, where *x* is the source of P as reported in Table 4.

describing a wide range of fertilization situations applied to different soils, with a good overall prediction capacity. In addition, through this model we could interpret some treatments in which a single linear or curvilinear interpolation would have failed, due to the limited variation in the P balance and high dispersion of the soil P status, such as in the Lm-Min and Cs-Fym treatments. Therefore, the exponential model can be used to interpret, generalize and forecast soil Olsen P trends following the adoption of different fertilization strategies, through the analysis of the optimized parameter values. Here, we analyse three fertilization strategies: suspension of fertilization, balanced supply and unbalanced supply. Then, we inspect the effect of soil and fertilizer types, also in interaction between them.

4.1 | Long-term consequences of fertilization suspension

The suspension of P fertilization will cause a negative balance that will force the crop exploit legacy P from pools where most soil total P is immobilized (Sucunza et al., 2018). The soil Olsen P concentration will progressively reduce. The exponential model shows that when the accumulated P balance approaches -∞, the Olsen P concentration will tend to an asymptotic value specific to each soil, that is coefficient *a*. It varied among the sites and was approximately 23 mg P kg^{-1} at Lombriasco and 0 mg P kg^{-1} at both Cussanio and Tetto Frati (Table 4). We recognize that P is a finite resource and that this makes parameter *a* more theoretical than real. Nonetheless, its value was not statistically different from zero at either Cussanio or Tetto Frati, while the value obtained at Lombriasco indicated that P should not be a growth-limiting factor at this site for a long time. The presence of an asymptotic level was also noticed by other authors (e.g., Ma et al., 2009; Messiga et al., 2015). Aulakh et al. (2007) and Zicker et al. (2018) also observed that the value of soil Olsen P without P supply first decreased, and then increased or remained constant. In our data set, two treatments (Ll-0 and Cm-0), after an initial depletion, showed a tendency to increase as a deficit grew. Unfortunately, our data were insufficient for analysis, but the phenomenon would benefit from further investigation.

4.2 | Long-term consequences of a balanced fertilization

When P supply equals P removal in the long term, that is, P balance is close to zero, Olsen P will in the long-term approach *a* + *b*. This means that soil available P reaches an equilibrium based on both soil and fertilizer characteristics. Coefficient *b* stands for the P source effect, based on the well-established fact that variation in soil available P is influenced by the source of P (Van der Bom et al., 2017; Edmeades, 2003; Shen et al., 2014). In our model, the absence of P fertilization was set as a reference (b_0 parameter), and parameters were created for the supply type used in each experiment (b_{Min}, b_{Org}, b_{OG}, b_{Fym} and b_{Slu}). The *b* value quantified the relative effect of different sources on soil P availability and ranked them as follows: farmyard manure > bovine slurry and green manure + organic fertilizers = absence of P supply > mineral fertilizers and organic fertilizers (MSW compost and digestate) (Table 4). When the accumulated balance was null, the use of farmyard manure drove soil Olsen P concentration 11.34 mg kg^{-1} above that measured in the zero P supply (24.96 mg kg^{-1}), while mineral or organic fertilizer use resulted in a soil Olsen P concentration of 6.99 mg kg^{-1} and −8.50 mg kg^{-1} below that attained with no P supply (Table 4).

4.3 | Long-term consequences of an unbalanced fertilization

The amount of soil available P for crops is regulated by a host of soil chemical, physical and biological factors (Ciampitti et al., 2011). Each of these aspects depends on soil type. An excessive fertilization will increase the soil reserves and affect the available pool size, whereas an insufficient level of supply will progressively deplete the available pool (Zhang et al., 2020). The exponential model tells us that the enrichment rate is different from the depletion rate on a linear scale with the P balance, and is indicated by a specific parameter – the *c* parameter – that is one of the components of the exponent in the function, a component that multiplies the P balance variable. The *c* parameter therefore represents the soil-dependent rate of decay or build-up of soil Olsen P. The higher the value of *c*, the more reactive is the soil to changes in the P balance. The model also informs us that the speed of the increase or decrease in Olsen P mainly depends on the soil characteristics. It was higher at Lombriasco than the other two soils (Table 4); therefore, Lombriasco showed a stronger response than Tetto Frati. This could be due to the fact that the calcareous Tetto Frati soil could buffer the Olsen P concentration to a larger extent (Liu et al., 2019), owing to the reaction of P with calcium carbonates, and according to the estimated values of *c*, the buffer capacity was nearly 7 times higher at Tetto Frati than at Lombriasco. The value of *c* did not differ significantly from zero at Cussanio. A value of zero sets to zero the exponent that includes the P balance; therefore, the accumulated P balance was deemed not to influence the dynamics of soil Olsen P; only the source of P supply did so at Cussanio.

A fertilization strategy based on reduced or excessive supply will therefore affect the Olsen P soil pool to a greater extent at Lombriasco, to a minor extent at Tetto Frati and to a negligible extent at Cussanio. The Cussanio result may stem from soil characteristics or be artefact consequent to an absence of high supply cases in our data set.

4.4 | Soil characteristics

Both *a* and *c* express the soil reactivity to changes in P balance, or in other words to soil P buffer capacity, a property that converts unavailable P pool into available P in depletion situations and *vice versa* in enrichment situations. Depending on soil characteristics, soil P buffer capacity can mask the relationship between soil Olsen P concentration and P balance, like at Cussanio (Ciampitti et al., 2011; Messiga et al., 2015; Zicker et al., 2018). The pH is the major factor that determines P adsorption on Fe and Al oxides under acidic conditions and P precipitation as Ca phosphates in neutral to alkaline soils (Hinsinger, 2001). Soil clay content also plays a role, as it is negatively correlated with changes in the status of soil available P (Cox, 1994). Therefore, the P buffer capacity of the young sandy-loam soil with an 8.1 pH and high $CaCO_3$ content at Tetto Frati was higher than that at Lombriasco, which had a loamy soil with a higher clay content, a pH of 6.2, and a high Fe and Al oxide content (data not shown). Data on the Fe and Al oxide contents at Cussanio were unavailable; however, the moderate clay content, greyish colour and neutral pH suggested the soil had a limited buffer capacity. Indeed, the Olsen P value at Cussanio reflected annual supply with fertilizer rather than a legacy of soil P. As the model was applied to three types of soils only, a further validation of this approach is needed.

4.5 | Fertilizer types

The soil Olsen P response to P supply in the same soil differed for each source of P and was quantified by *b* parameter in the exponential model. Parameter *b* represents the amount of available P when the balance is at equilibrium, given a particular soil supply as represented by parameter *a*. Differences in the *b* parameter values related primarily to the quantity and quality of organic matter supplied by the different sources that released P after mineralization.

The *b* reference value (b_0) referred to the treatment with no supply of P and is theoretically linked to the transformation of unavailable into available P forms. The values of b_{Fym}, b_{Min} and b_{Org} differed significantly from b_0, but b_{Slu} and b_{OG} did not. That b_{Min} resulted as lower than b_0 indicated that the variation in Olsen P caused by mineral supply was less than the variation in the measure because of the absence of fertilization. This suggests that mineral fertilization, due to the fixing phenomenon, is limited in its ability to build the available P pool. Colomb et al. (2007) reported that 90%–92% of P supplied with mineral fertilizers in excess of crop removal was transferred into a non-available pool. Some authors, such as Paris et al. (2004) and Zicker et al. (2018), recorded decreases in soil Olsen P, despite a surplus of mineral P supply.

The finding that b_{Org} was lower than b_0 showed that in the long term, compost fertilization did not benefit available P. However, in the medium term, the linear model results revealed that the compost supplied at Lombriasco provoked an increase in soil Olsen P, regardless of high or low initial concentration. This result agreed with reports by Evanylo et al. (2008) that soil available P increased with the application of compost, compared with unfertilized and mineral P treatments in the short term. The study by Moretti et al. (2020) at Lombriasco reveals that municipal solid waste (MSW) compost increased the most labile SOM fractions that are responsible to short-term P dynamics here outlined using the linear model, but did not increase the SOM stable fractions.

Values b_{OG} and b_{Slu} were similar to the b_0 value, suggesting that both green manure, even if added to composted commercial organic fertilizers, and bovine slurry resulted as similar to the treatment that received no P fertilizer. The resulting parameter at each treatment, that is the $b_0 + b_x$ value, where x is the type of P source, changed with the C:P ratio of the different matrices (Figure 6). The relationship was highly non-linear, and an exponential function in the same form as (1) well-fitted data, despite the paucity of cases does not allow for a further data analysis. However, the higher the C:P ratio, the higher the value of *b*, this meaning that organic C in the supply promoted the availability of added P. Damon et al. (2014) also observed that mineralization of fresh crop residue mineralization (green manure) increased with its C:P ratio, and argued that soil microorganisms are stimulated by the addition of matrices with a high C content, leading to a higher incorporation and subsequent mineralization of microbial biomass P, that at the end increases the plant-available fraction. In contrast, Jalali (2009) and Lupwayi et al. (2007) reported that the P released from plant residues or from organic P fertilizers was positively correlated with P concentration, but negatively correlated with the C:P and lignin:P ratio of the P source. The absence of an increased soil Olsen P concentration in the Cm-OG treatment, despite a surplus of *c*. 380 kg P ha^{-1} after 12 years, may be attributed to the low P amount released by mineralization of added matrices. As much as 80%–98% (Espinosa et al., 2017) of crop residue P can remain in organic forms and go undetected by the Olsen method. Not only does green manure fail to support available P pool build-up, but it also scarcely contributes to an increase in SOM content. Actually, it is more akin to a mineral fertilizer than to an organic one (Sacco et al., 2015). Bovine slurry also contains a large fraction of inorganic of P (Hansen et al., 2004), which caused it to fix quickly into non-available P form pools like P mineral fertilizers.

Only the farmyard manure P supply raised the concentration of soil Olsen P, which may be attributed to the P contained in organic compounds that ensured a slow, but efficient release of easily available P. It can also be mediated by increased phosphatases in the rhizosphere (Shen et al., 2014) or by development of microorganisms that foster stable SOM mineralization (Van der Bom et al., 2017). Manure mineralization involves formation of soluble organic phosphate compounds and organic acids that reduce P adsorption on Fe and Al oxides (in soils where this process prevails), and Ca-fixing compound solubilization in alkaline soils. Both processes lead to an increased P availability for crops (Jalali, 2009; Von Wandruszka, 2006; Zhu et al., 2018).

5 | CONCLUSIONS

We confirmed that accumulated P balance is a good and powerful predictor of soil Olsen P dynamics in the long term, making it possible to compare experiments that differ in P supply, as well as in crop, crop uptake and duration. This study allowed us to answer positively to the research questions we posed.

An exponential model fitted well to soil Olsen P data of three long-term experiments spanning a wide range of fertilization management situations, using the accumulated P balance as the explanatory variable. Hence, we propose to apply this model to other field trials to verify its robustness to predict the long-term dynamics of soil available P response.

Pooling all experimental treatments together allowed to interpret situations that a single interpolation would have failed to relate to P balance. The exponential model supported a generalizable agronomic interpretation of all optimized parameters. The fundamental role that soil characteristics play in the response of soil Olsen P to different P supply sources was evident, in particular concerning the constant level achieved in the soil as soil cumulative P balance approached $-\infty$ (parameter *a*). This observation makes clear that extension agents, practitioners, but also P fertilizer-recommendation tools need to take different soil types into account when considering thresholds above which fertilization should be suspended. The soil Olsen P response was also influenced by P source (parameter *b*). Specifically, P sourced from farmyard manure increased the available P pool to a greater extent than either other organics (bovine slurry, commercial organic fertilizers, green manure) or inorganic fertilizers, due to its high C/P.

Additional studies on how to predict soil response from soil characteristics will give better insight into the capacity of a depleted soil to utilize legacy P to sustain crop uptake. Further investigation is also needed to forecast the behaviour of fertilizers and other organic matrices from some easily recoverable information, such as the C:P or lignin:P ratios.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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