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Rationality of using phosphorus primary and secondary sources in circular economy: Game-theory-based analysis

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ABSTRACT

European Union (EU) faces serious disturbances in the supply of phosphorus. To tackle this problem, the Member States have started practicing the principles of circular economy in the management of phosphorus supply chain. A decision to select either primary or secondary sources of phosphorus is one of the major dilemmas in the application of these principles. In this paper, the Bayesian and Nash Equilibrium games are used to analyze the selection of primary or secondary sources of phosphorus in Europe (EU-27), under the condition of supply deficit. The objective of this analysis is to determine the conditions for the use of primary or secondary source. We examined situations of the so called low or high deficit. According to the principles of circular economy, the use of secondary sources is always preferred, and everyday practice shows that it is also rational, under conditions of low deficit. The rationality is justified by the sufficient time an enterprise has got to react. However, in the situation of high deficit, the lack of time makes the use of primary sources a rational decision. In short, rational decision means to opt for using secondary sources when deficit is low and primary sources when the deficit is high. The analysis of phosphorus supply over 15 years, 2002–2017, shows that only the Netherlands made a rational decision with the probability higher than 0.8. The analysis indicates that even if in the next 12 years recycling increases to 50 % of phosphorus supply, it will not improve the rationality of decisions on the use of secondary sources of phosphorus in Ireland, Portugal, Spain, Italy, Poland, Romania, Greece, Malta, and Cyprus. The main finding of this paper is the conclusion that the improvement of recycling technology will not improve the rationality of decisions on the use of secondary sources of phosphorus in several countries. It means that the problem is not the recycling technology itself but the policy pursued vis-à-vis using the primary or secondary sources.

1. Introduction

Phosphorus (P) is a non-renewable resource essential for human life. It is crucial for the food chain and health of the population. Europe is a region with few substantial reserves of phosphate ores. This shortage of mineral phosphates in Europe makes phosphorus sensitive to any risk emerging in its life cycle. The European Commission identified high dependency on imported phosphorus reaching almost 88 %, (EU Commission, 2017a). Such a high level of reliance on phosphorus imports produces geopolitical tensions for the European governments and firms (Van Dijk et al., 2016). The management policy of phosphorus supply chain in Europe is based on national policies of the Member States which differ with respect to economic benefits and environmental impact as well as resource scarcity and the advancement in the implementation of circular economy model (Stahel, 2016). In addition, the motivation for sustainable use of phosphorus in Europe is driven by the aspiration to implement the principles of circular economy (Golroudbary et al., 2019; Nesme and Withers, 2016). Therefore, recycling or recovery of phosphorus from waste streams has been proposed as a possible approach to managing its sustainable use. The circularity of phosphorus supply chain is an objective of the EU policy as it offers a possibility to satisfy phosphorus demand and reduce the dependence on imports (EU Commission, 2017c). Hence, the main objective of this paper is to examine decisions made by the EU-27 with regard to phosphorus recycling under conditions of supply deficit.

The concept of circular economy is a tool adopted to tackle the supply risk of critical materials in the first place. Dramatic change in resource consumption urges policymakers to shift from linear resource use to a circular one. It is a sustainable alternative to linear economic models, where the value of materials is meant to be recovered within the system (Ranta et al., 2018). There are various definitions for circular economy, however, recycling is always a prominent feature of the concept (Kalmykova et al., 2018; Kirchherr et al., 2017).

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Phosphorus life cycle in Europe is a perfect case for the transition from linear to circular economy (Mehr et al., 2018). Circular economy provides opportunities for sustainable use of phosphorus given the high potential of recovery and recycling in the supply chain are ensured (Withers et al., 2018). In Europe, improving phosphorus recycling can potentially decrease the reliance on mining and imports by up to 79 % (El Wali et al., 2019). Therefore, implementation of a full circular economy in the phosphorus manufacturing sector by increasing recycling and improving sustainable management of phosphorus is one of the top priorities of the European Union (EU), as emphasized in the EU 2020 Strategy (Fischer and Kjaer, 2012; Kanter and Brownlie, 2019).

The comprehensive framework of circular economy concept considers three perspectives on the supply chain including environmental impact, economic benefits and resource scarcity (Lieder and Rashid, 2016). Interestingly, in the phosphorus supply chain, this circular economy framework does not necessarily trigger the same strategy in different countries in Europe (Scholz and Wellmer, 2018). For instance, some countries such as Denmark, Sweden, the Netherlands, Germany and Switzerland see a potential impact of using secondary sources on the decreasing dependency on phosphorus mining and imports in line with the sustainability of the supply chain (Fischer and Kjaer, 2012; Schoumans et al., 2010; Schroder et al., 2010). On the other hand, for France and the UK, this alternative does not substantially increase the efficiency of the phosphorus supply chain (Brownlie et al., 2014; Jedelhauser and Binder, 2015). In other words, there is no coordinated international strategy for sustainable recovery of phosphorus (Cordell et al., 2011; Jacobs et al., 2017).

In this paper, we distinguish between primary and secondary phosphorus sources in Europe. In our study, primary sources include mined and imported phosphorus. Secondary sources are mainly recycling of waste from food and non-food sectors. There are challenges behind using phosphorus from either primary or secondary sources of supply. Generally, providing phosphorus from primary sources in Europe is always conditioned by uncertain circumstances such as the changing price and scarcity of the material. On the other hand, recycling of phosphorus also generates various challenges such as technical difficulties (e.g., its low recovery rate), logistics (e.g., access to sufficient volumes of adequate quality recycled phosphorus), economics (e.g., cost of recycled phosphorus), production process (e.g., open loop or closed loop processes), and time (e.g., delay in mobilization of the required amount of phosphorus) (Metson et al., 2015). Of all these, the economic challenges are arguably the greatest limitation. For instance, current technologies are not yet advanced enough to recycle more than 50 % of phosphorus from wastewater in economically viable way (Scholz and Wellmer, 2018). In fact, the cost of phosphorus recycling from wastewater is significantly higher than its extraction from phosphate rock ores (Mayer et al., 2016; Molinos-Senante et al., 2011). Also, impurities in recycled phosphorus make industries use more costly technologies to reduce them to the desired level (Sarvajayakesavalu et al., 2018). However, there are several environmental reasons that drive decision makers towards the use of secondary resources of phosphorus. For example, a linear phosphorus supply chain leads to the spreading of P element into aquatic ecosystems, which contributes to water pollution, known as eutrophication (Tangsubkul et al., 2005). The EU Member States are equally committed to decrease the level of water eutrophication to a certain extent (Strömbäck et al., 2018). By extension, this refers to the recovery of P element from water bodies and using it as a secondary resource for land fertilization (Kabbe, 2015).

Various potential solutions to phosphorus challenges are proposed from different perspectives: scientific (Schroder et al., 2010; Withers et al., 2015b), political (EU Commission, 2010, 2014, 2017b) and business (Schipper, 2014; Withers et al., 2015a). These solutions include efficient and effective use of phosphorus in society with the intention to improve recycling. However, there is a lack of research that would examine decision-makers' behavior with regard to using different sources of phosphorus under conditions of supply deficit. The main problem lies with decision-makers whose behavior is strategic for the choice of either primary or secondary sources of phosphorus supply. In general, when the deficit is high, feasible action consists in using primary sources due to the time needed to mobilize the required amount of phosphorus.

The aim of this paper is to carry out a behavioral analysis of the decision-making process related with using primary or secondary sources of phosphorus. The interaction of decision makers with the phosphorus supply chain is complex, which is why these decisions are never identical. They are made in the context of the above-mentioned perspectives, i.e., economic benefits and environmental impact, as well as resource scarcity and the implementation of circular economy model (Stahel, 2016). Hence, the main objective of this paper is to examine decisions made by the EU-27 with regard to phosphorus recycling under circumstances of supply deficit. This study targets countries the 27 EU Member States. We analyzed phosphorus flows in the period 2002–2017 mainly based on the EU Commission and other research data sources, such as El Wali et al. (2019) and Van Dijk et al. (2016). Croatia joined the European Union as its 28th member state on 1 July 2013. Therefore, the quantification of phosphorus flows in Croatia was not feasible due to the unavailability of data.

Our study uses game theory to investigate past practices of the EU member states in using primary or secondary phosphorus sources. In addition, we developed a game model to predict the intentions of decision makers in using phosphorus recycling in the next 12 years.

Based on the game theory, players who are decision makers in phosphorus supply in country *i*, face a dilemma what sources of supply they should use: primary or secondary. The situation gets more complicated under changing supply levels of phosphorus. We view the availability of phosphorus in the market against two predefined levels: low and high deficit. As previously mentioned, the use of secondary sources is rational in conditions of low deficit. Therefore, decision makers intend to cooperate in using phosphorus recycling. On the other hand, under conditions of high deficit the decision makers have to minimize the time needed to mobilize the required amount of the material therefore, they prefer using primary sources and decisions are made to ensure quick supply of required phosphorus in a non-cooperative behavior.

In this study, game theory is used to help in understanding the decision-makers interactions. This method uses models as highly abstract representations of various types of real-life situations (Osborne and Rubinstein, 1994). The generality of models in game theory allows using them across a wide range of areas. For example, Leng and Parlar (2010) assume that a manufacturer faces a random price-dependent demand in either additive or multiplicative form. They analyzed the Nash equilibria for this case and found a globally-optimal solution that maximizes the system-wide expected profit. Zhao et al. (2012) used game theory to limit environmental burden within the supply chain by focusing on the strategies selected by manufacturers to reduce life cycle environmental risk of materials and carbon emissions. Yue and You (2014) analyzed Nash equilibrium in multi-echelon supply chains. They considered county-level case study for a potential biofuel supply chain.

2. Materials and methods

El Wali et al. (2019) and Van Dijk et al. (2016) quantified the material flow within the phosphorus supply chain in each member state of the EU-27, and El Wali et al. (2019) show the current level of recycling of various waste streams (solid waste, water treatment and manure). They estimated the possible improvement of economic recycling and its impact on the criticality of phosphorus in Europe. This information provides input data for estimating the probability of using phosphorus recycling in the EU.

Phosphorus flows for EU-27 are examined mainly across production sectors such as agriculture, animal, food and non-food, as well as human consumption. Fig. 1 shows a conceptual overview of primary and secondary phosphorus production in linear and circular economy. There are different streams of material flows (e.g., imports, domestic sources, primary and secondary production, exports, consumption and losses) used in several industries, e.g., food and non-food industries.

Table 1 shows inflows of material and their sources of supply in different sectors of phosphorus supply chain. Table 2 lists the outflows of material from different sectors to their destinations in the supply chain. Next, we described the features and processes that are central to the understanding of the main input data for the designed game.

2.1. Mining and processing

The first stage of the phosphorus supply chain starts with the mining process of phosphate rock. This stage is followed by sub-phases where the mined material is further enriched ("beneficiated") and processed into pure phosphoric acid (Koppelaar and Weikard, 2013). Phosphoric acid is used in the production of fertilizers and in other purified phases of phosphorus. Purified phosphorus is used for the production of non-food products, such as detergents and other chemicals, while fertilizers are used for the crop production (Scholz and Wellmer, 2015a).

2.2. Production and consumption

Phosphorus is mainly used in agriculture as a component of fertilizers (Belboom et al., 2015). In addition, some amounts of phosphorus originating from atmospheric deposition enter the soil as a natural fertilizer (Chen and Graedel, 2016). Being raw material for other food and non-food industries, crops grown on such soil go through different phases of the supply chain including animal, food and non-food production sectors (Mottet et al., 2017; Noya et al., 2017). Animal production uses crops for feeding livestock and poultry and delivers dairy products and commodities for the food processing sector. It also supplies the non-food sector with animal-based materials, such as wool and hair. The food production sector deals with the processing of crops into food commodities which are later offered for human consumption. Finally, the non-food production sector covers non-food crops, such as plant-based products and forestry products (Van Dijk et al., 2016), as well as the production of laundry detergents and other industrial

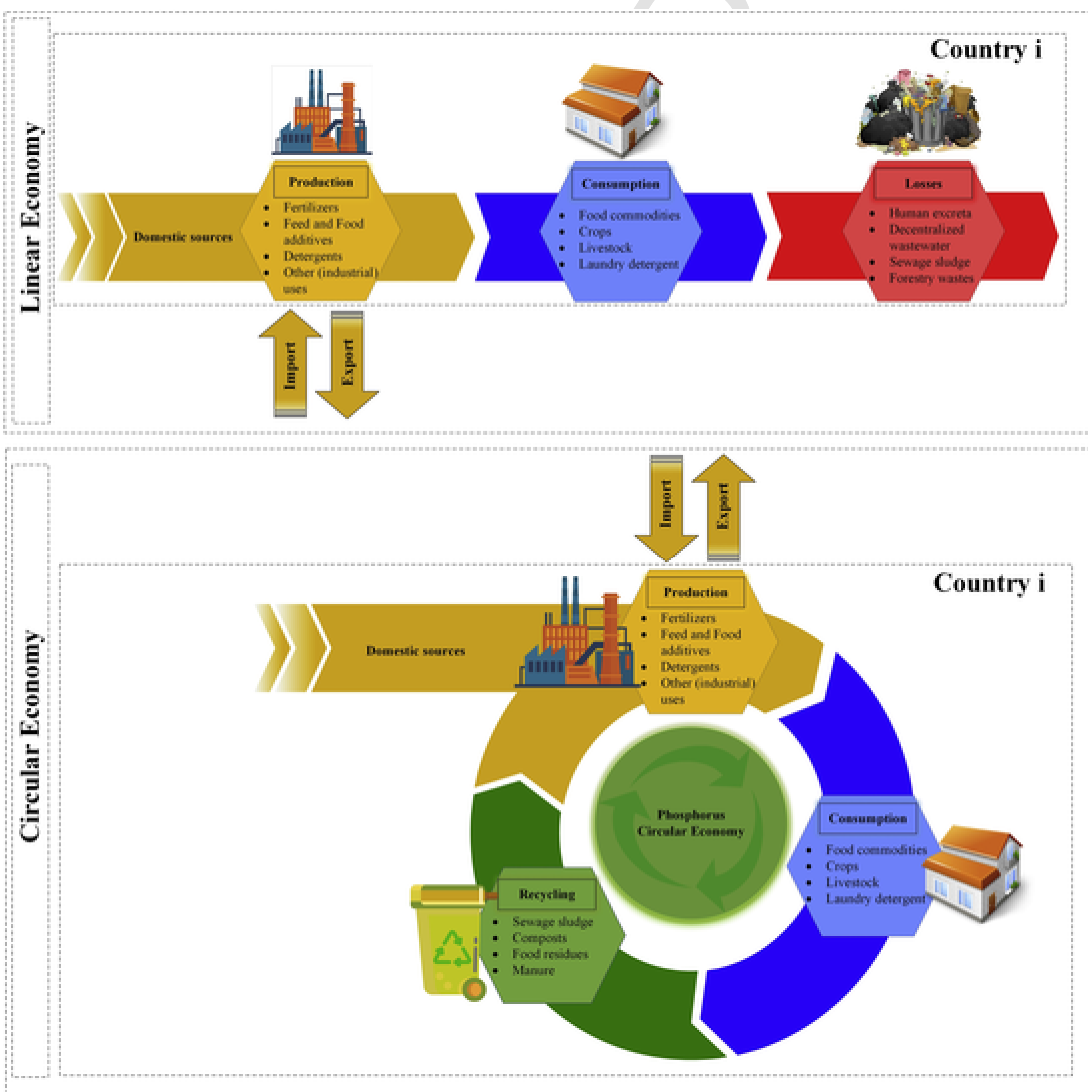

Fig. 1. Conceptual overview of linear and circular economy for phosphorus supply chain.

Table 1
Inflows of phosphorus through its supply chain (El Wali et al., 2019; Scholz and Wellmer, 2015b; Van Dijk et al., 2016).

Stage	Linear Economy		Circular Economy	
	Flow	Source	Flow	Source
Agriculture production	Inorganic fertilizers	Fertilizers production from mined phosphorus	Communal sewage sludge	Human consumption
	Seeds	Imports	Communal compost	Human consumption
	Planting material	Imports	Recycled compounds	Human consumption
	Mineral fertilizer	Imports	Manure	Animal production
	Pesticides	Imports	By-product fertilizers	Food production
			Recycled organic fertilizers	Non-food production
Animal production	Feed crops	Agriculture production	Feed from residues	Human consumption
	Plant-based feed	Imports	Feed from non-food materials	Non-food production
	Animal-based feed	Imports	By-product feed products	Food production
	Feed additives	Imports		
Food production	Crops	Imports	Food residues	Human consumption
	Slaughtered livestock	Imports	Food and beverage ingredients	Non-food production
	Fish catches	Imports		
	Food additives	Imports		
	Food crops	Agriculture production		
	Slaughtered livestock	Animal production		
	Eggs	Animal production		
	Milk	Animal production		
Non-food production	Plant-based materials	Imports	Recycled forestry products	Human consumption
	Animal-based materials	Imports		
	Detergents	Imports		
	Forestry products	Imports		
	Chemical products	Purified phosphorus from mining		
	Detergents	Purified phosphoric acid		
	Non-food crops	Agriculture production		
	Wool and hair	Animal production		

Table 2
Outflows of phosphorus through its supply chain (Chen and Graedel, 2016; El Wali et al., 2019; Van Dijk et al., 2016).

Stages	Flow	Destination
Agriculture production	Seeds and planting material	Exports
	Runoff, erosion	Losses
	Feed crops	Animal production
	Food crops	Food production
	Non-food crops	Non-food production
Animal production	Plant-based feed	Exports
	Animal-based feed	Exports
	Livestock	Exports
	Manure	Exports
	Feed waste	Losses
	Slaughtered livestock	Food production
	Eggs and milk	Food production
	Wool and hair	Non-food production
Food production	Crops	Exports
	Slaughtered livestock	Exports
	Slaughtered waste	Losses
	Food processing waste	Losses
	Food products	Human Consumption
	Food additives	Human Consumption
	Pet food ingredients and by-products	Non-food production
	Food residues	Non-food production
Non-food production	Plant-based and animal-based materials	Exports
	Forestry products	Exports
	Industrial wastes	Losses
	Forestry products	Human consumption
	Household detergents	Human consumption
	Pet food	Human consumption
	Plant and animal-based products	Human consumption
Human consumption	Human excreta	Losses
	Wastewater	Losses
	Food waste	Losses
	Decentralized wastewater	Losses

uses (Van Hoof et al., 2017). Commodities and goods produced by all these sectors are intended for human consumption which covers food and non-food commodities. Food commodities include plant-

Table 2 (*Continued*)

Stages	Flow	Destination
	Forestry wastes	Losses
	Communal sewage sludge	Losses
	Communal sewage sludge	Agriculture production
	Communal compost	Agriculture production
	Recycled compounds	Agriculture production
	Feed from food residues	Animal production
	Food residues	Food production
	Recycled forestry products	Non-food production

based products, animal-based products and food additives. Non-food commodities include household detergents, plant-based materials, animal-based materials, pet food and forestry products.

2.3. Recycling

In the phosphorus supply chain, recycling takes place throughout the production process until the post-consumption stages. During the non-food process, waste is recycled and reused for agriculture, food and animal production. Those recycled materials include organic materials, food additives and animal feed. In food processing, waste is recycled to be used as fertilizers and animal feed (Cordell et al., 2013). During the process of animal production, waste is recycled to be used as manure for land fertilization and crop production (Haase et al., 2017). In the post-consumption stages, phosphorus waste is recycled and reused in different sectors including crop production (e.g., for organic fertilizers), animal production (e.g., for food residues and animal feed), food processing (e.g., for food residues and food additives), and non-food production (e.g., for paper and wood).

2.4. Losses

Losses occur throughout the phosphorus supply chain under different circumstances (Chen and Graedel, 2016). A significant amount of phosphorus is lost through runoff and leaching during crop production (Fowdar et al., 2017). In addition, some phosphorus is lost in waste from animal, food and non-food production. In the post-consumption stages, losses of phosphorus occur because P is lost in food waste, human excreta, wastewater effluents, non-food waste such as paper, wood and industrial waste, and composted waste for non-agricultural uses.

2.5. Imports and exports

Imports and exports are trade activities carried out by the EU and its Member States. This study examines trade flows of the material for each Member State separately and for the EU as a whole. Imports and exports occur in all production phases in the phosphorus supply chain including agriculture, animal, food and non-food production (Tables 1 and 2). The EU imports around 6 million tons of natural phosphate annually. Most of EU imports come from Morocco (30–35 %) and Russia (14–20 %), followed by Algeria, Israel, and South Africa. Moreover, the EU imports around 1.2 million tons of phosphate fertilizers annually, from Russia, Morocco and Tunisia.

2.6. Methodology

Generally, components of the game include a) players who are rational agents and participate in the game trying to maximize their payoff; b) strategy which is an action that a player can choose to follow from a set of possible actions in every conceivable situation; c) strategy profile which is a list of strategies for all players in a game with only one strategy for each player; d) order of play which shows that players may move simultaneously or sequentially; e) information set which shows what a player knows about previous actions; f) outcome of the game for each set of actions by the players; g) payoff which is the preference that a player receives depending on the chosen strategy profile (the performance metric is called "payoff function" in case of maximizing the profits, or "loss function" in case of minimizing the cost). Depending on the interaction among different game players, the game is classified as a cooperative or non-cooperative one with each type representing different strategic behavior.

In our game, strategic behavior refers generally to actions undertaken by the EU decision makers and intended either to encourage rivals to act cooperatively to raise joint profits (cooperative actions) or to boost the country's profits at the expense of its competitors (non-cooperative actions).

In the case of phosphorus supply chain in Europe, with this complex system in mind, we consider each country as a player exhibiting different strategic behavior. The target countries are 27 EU Member States, including Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

Bayesian and Nash Equilibrium games are implemented and solved to ensure the rational use of primary and secondary sources of phosphorus supply in Europe. Below, we will explain those games in detail. Notations used in our game can be found in Table 3.

2.6.1. Bayesian game for phosphorus life cycle in different countries in Europe

In this step we proceed to investigate the life cycle of phosphorus in line with circular economy model practiced at national level in Europe. Our assumption is that all decision makers (players) in each country are independent. Their role is to make a decision regarding the supply of phosphorus based on the knowledge they have from historical data about the probability of phosphorus availability from primary sources (i.e., imports and mining) and from secondary sources (i.e., recycling). The decision makers may interpret the historical information in different ways. Based on their interpretation, each player chooses either primary or secondary source or both sources as a way to meet the demand for phosphorus of her/his respective country. Therefore, we classify the players' decisions as either single material-based (virgin or recycled phosphorus) or mixed sources-based decisions.

As explained in the Introduction, players sometimes prefer to avoid using recycling as the first option due to the above-mentioned challenges involved in the process, as well as faster access to primary sources. However, given the political agreement behind the EU Commission's circular economy and recycling strategies, we assume that each player a priori believes that there is a benefit for Europe to provide phosphorus from secondary sources with probability π (the same for every decision maker), a belief modified by historical information.

First, we model the possibility that decision makers interpret past circumstances differently when choosing the best supply option (virgin or recycled phosphorus) for each country. Each decision maker interprets historical information concerning the selection of primary or secondary sources with positive probability and their interpretations

Table 3
Game variables and notation.

Symbol	Meaning
X_i^{TD}	Total phosphorus demand in country i (Tonnes P·year $^{-1}$)
X_i^{ES}	The existing supply of phosphorus in different sectors of production including agriculture, animal, food and non-food (Tonnes P·year $^{-1}$)
X_i^{D}	Phosphorus deficit in country i (Tonnes P·year $^{-1}$)
p_i	Initial probability of supplying phosphorus from primary sources for country i (Dimensionless)
q_i	Initial probability of supplying phosphorus from secondary sources for country i (Dimensionless)
c	Bernoulli payoff of choosing primary or secondary sources (Dimensionless)
u_1	Probability of choosing secondary sources of phosphorus based on a prior belief of a decision maker (player) and a signal received from the market (Dimensionless)
u_2	Probability of choosing primary sources of phosphorus based on a prior belief of a decision maker (player) and a signal received from the market (Dimensionless)
V	Virgin phosphorus (Tonnes P·year $^{-1}$)
R	Recycled phosphorus (Tonnes P·year $^{-1}$)
D_V	Decision for using virgin phosphorus (Dimensionless)
D_R	Decision for using recycled phosphorus (Dimensionless)
H	High-level deficit (Dimensionless)
L	Low-level deficit (Dimensionless)
A	The availability of phosphorus in high or low deficit of P market (Dimensionless)
s_i^A	A signal that a decision maker (player i) receives in the state A (Dimensionless)
a_i	Set of actions for player i (Dimensionless)

are independent. It means that the interpretation of one decision maker does not depend on the interpretation of any other.

To present a clear picture of the phosphorus market in Europe, first we need to define demand. In this study, demand for phosphorus in country i is defined by the Eq. 1.

$$X_i^{TD} = X_i^{ES} + X_i^{D} \quad (1)$$

where X_i^{TD} corresponds to the total demand for phosphorus in country i ($i = 1, \ldots, 27$). Existing supply (X_i^{ES}) represents the amount of phosphorus available in different sectors of production (agriculture, animal, food and non-food) in country i ($i = 1, \ldots, 27$). Deficit of phosphorus is represented by X_i^{D} for country i ($i = 1, \ldots, 27$).

The probability of phosphorus availability from each source is a signal in our game. It is a dynamic value due to the changing level of deficit. We consider that, due to historical data, probabilities are the same for all decision makers. The main assumption is that probability of any given decision maker's interpretation based on the historical information for selecting primary sources of phosphorus supply when market deficit is high is given by p and for selecting secondary sources when market deficit is low is given by q.

Next, we formulate a Bayesian game that models the situation. In this game, each player's action is a decision about choosing either virgin (V) or recycled (R) phosphorus. We need one state for each configuration of the players' preferences and information. Each player's preference depends on whether phosphorus is available from these sources. Also, their knowledge includes the interpretation of historical data. Therefore, we define a state, where A corresponds to the availability of phosphorus from both sources.

The level of deficit including high (H) and low (L) is considered a signal for players. s_i^A ($i = 1, \ldots, 27$ and $A = H, L$) is the interpretation of a player i based on historical data, which may consider recycling as the best option when market deficit is low or virgin material as the best option when the market deficit is high. In any state in which $A = H$ (i.e., the state when more than 50 % of the total demand for phosphorus is not available in the production sectors), each player assigns probability p to any other player receiving the H signal, and probability $1 - p$ to the players who are receiving the L signal, interdependently of all players' signals. Similarly, in any state in which $A = L$ (i.e., the state when less than 50 % of the total demand for phosphorus is not available in the production sectors), each player assigns probability q to any other player receiving the L signal and probability $1 - q$ to the players who are receiving the H signal, interdependently of all players' signals.

If we assume that a decision maker is indifferent as to choosing between primary and secondary source, C c corresponds to relative weightings on the decision maker's threshold for making a wrong decision in this case (i.e., the cost of using primary or secondary sources when they are not the best option). We assume μ is the probability of choosing primary sources based on the decision maker's trust in a given signal. Every decision maker chooses primary source if its payoff is higher than that of the secondary source. Hence, a decision maker selects virgin phosphorus if and only if: $c \leq \mu_i$ and recycled phosphorus if and only if: $c \geq \mu_i$.

2.6.2. Bayesian game for phosphorus life cycle in Europe

We defined the supply chain of phosphorus as a system. The input into the system includes mining, import, production, and recycling. The output of the system includes losses, consumption and export. All considered P flows have been presented in Tables 1 and 2. The required variables are defined to examine the probability of using primary and secondary sources of phosphorus under the conditions of supply deficit.

In this game, we assume all players are the members of one committee as decision makers in Europe. In this case, our assumption is that majority decisions are required for selecting recycling sources. It means for n ≥ 2 players, only the action profile $(V_1, \ldots, V_i; R_1, \ldots, R_j)$ if $i < j$ ($i = 1, \ldots, 27$ and $j = 1, \ldots, 27$) leads to opting for phosphorus recycling. For example, if the number of decisions in favor of using virgin phosphorus is lower than those favoring recycling, then recycling will be considered as optimal decision. We assume that the selection of the best option in decision-making is influenced by several factors such as the volume, quality, environmental considerations and cost for the system. Therefore, in this process, each committee member has got a threshold for using primary sources when recycling is the best option and using secondary sources when the virgin phosphorus is the best option. The member of committee must also consider the likely effect of his decision on the outcome, which depends on other players' decisions. For example, a player who thinks his decision for using secondary sources is pivotal, may act differently from the one who is sure that the majority of his colleagues decide in favor of using primary sources of phosphorus. Therefore, an answer to the question requires us to consider the strategic interaction between the committee members, which may be modeled as a Bayesian game.

The Bernoulli payoffs function of each player in the Bayesian game for phosphorus life cycle in Europe is defined by Eq. 2 as follows:

$$u_i(D, A) = \begin{cases} 0 \; if \; i < j \; in \; (D_{V1}, \ldots, D_{Vi}; D_{R1}, \ldots, D_{Rj}) \; and \; A = L \; or \\ \quad if \; i > j \; in \; (D_{V1}, \ldots, D_{Vi}; D_{R1}, \ldots, D_{Rj}) \; and \; A = H \\ -c \; if \; i > j \; in \; (D_{V1}, \ldots, D_{Vi}; D_{R1}, \ldots, D_{Rj}) \; and \; A = L \\ -(1 - c) \; if \; i < j \; in \; (D_{V1}, \ldots, D_{Vi}; D_{R1}, \ldots, D_{Rj}) \; and \; A = H \end{cases} \quad ($$

where, u_i represents probability of choosing primary sources based on a prior belief of the decision maker and the signal received from market; D corresponds to decision of the player; D_{Vi} denotes a decision to use virgin phosphorus made by each country and D_{Rj} denotes a decision to use recycled phosphorus made by each country ($i = 1, \ldots, 27$ and $j = 1, \ldots, 27$); A corresponds to the availability of phosphorus; L represents low level of phosphorus deficit; H represents high level of phosphorus deficit; c corresponds the financial threshold for a non-optimal decision (i.e., the cost of using primary or secondary sources when they are not the best option).

Table 4 provides a numeric example of the proposed game. Considering Equation 2, c value is between μ_1 and μ_2.

The probability of making decision for using virgin phosphorus in the circumstances of low and high deficit of market is calculated as follows (Eqs. 3 and 4):

$$\mu(D_{Vi}\Big|L) = \frac{(1-p_i)\pi}{(1-p_i)\pi + q_i(1-\pi)} \tag{3}$$

$$\mu(D_{Vi}\Big|H) = \frac{p_i\pi}{p_i\pi + (1-q_i)(1-\pi)} \tag{4}$$

where, μ is probability of choosing sources based on a prior belief of a decision maker and a signal received from the market; D_{Vi} denotes a decision to use virgin phosphorus by country i; π represents a prior belief of a decision maker that virgin or recycled phosphorus should be used; L represents low level of phosphorus deficit; H represents high level of phosphorus deficit. In any state, probability p_i is assigned to any player using virgin phosphorus after having received the H signal, and probability $1-p_i$ to the players who are receiving the L signal, interdependently of all players' signals. Similarly, in any state probability q_i is assigned to any player using recycled phosphorus after having received the L signal and probability $1-q_i$ to the players who are receiving the H signal, interdependently of all players' signals.

2.6.2.1. Bayesian Nash equilibrium for phosphorus life cycle in Europe In game theory, "the Nash equilibrium is a solution concept of a non-cooperative game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only their own strategy." (Osborne and Rubinstein, 1994)A Bayesian Nash Equilibrium (BNE) is a set of strategies, one for each type of player, that generates no incentive to the players to change their strategies given the beliefs about other types of players and about what they are doing (Harsanyi, 1967). According to Osborne and Rubinstein (1994), a BNE is the Nash equilibrium of the strategic game which includes three main components (Eq. 5): a) the set of players, if all pairs (i, s_i), where i is one of the players and s_i is one of the signals that the player may receive in state A ; b) the set of actions (a_i) of each player (i, s_i) in the Bayesian game; c) the expected payoff for player i when signal s_i is received and action a_i is chosen.

$$\left(a_i,\ s_i\right) = \sum_{i=1}^{n} \mathrm{Prob}\left(\mathrm{A}|s_i\right) u_i\left(\left(a_i, \hat{a}_{-i}\left(\mathrm{A}\right)\right), \mathrm{A}\right) \tag{5}$$

Table 4
Probability of choosing primary and secondary sources of phosphorus.

No.	Country	Shortage level	p_i	q_i	μ_1	μ_2
1	Austria	Low	0,61	0,63	0,78	0,90
2	Bulgaria	Low	0,68	0,60	0,75	0,91
3	Belgium	High	0,86	0,55	0,58	0,92
4	Cyprus	High	0,62	0,41	0,84	0,85
5	Czech Republic	Low	0,58	0,73	0,77	0,92
6	Germany	Low	0,60	0,66	0,78	0,91
7	Denmark	High	0,72	0,52	0,75	0,90
8	Estonia	Low	0,69	0,65	0,73	0,92
9	Greece	High	0,73	0,33	0,82	0,86
10	Spain	High	0,63	0,42	0,83	0,86
11	Finland	High	0,81	0,34	0,76	0,87
12	France	Low	0,61	0,63	0,78	0,90
13	Hungary	Low	0,85	0,64	0,57	0,93
14	Ireland	High	0,42	0,65	0,84	0,87
15	Italy	High	0,64	0,45	0,82	0,87
16	Lithuania	Low	0,66	0,60	0,76	0,90
17	Luxembourg	High	0,65	0,63	0,76	0,91
18	Latvia	Low	0,66	0,64	0,75	0,91
19	Malta	High	0,61	0,41	0,84	0,85
20	Netherlands	High	1,00	0,57	0,04	0,93
21	Poland	High	0,67	0,39	0,82	0,86
22	Portugal	High	0,64	0,40	0,83	0,86
23	Romania	Low	0,49	0,59	0,83	0,87
24	Sweden	High	0,72	0,51	0,76	0,89
25	Slovenia	High	0,66	0,54	0,78	0,89
26	Slovakia	Low	0,61	0,81	0,73	0,95
27	UK	High	0,50	0,58	0,83	0,87

3. Results and discussion

In this section, first, we present the results of Bayesian game for phosphorus life cycle in different countries in Europe. Then, we discuss the results of BNE for the EU acting as one committee.

The results show the range of probability for making a rational decision regarding phosphorus supply based on given signals (low and high deficit) for each country in Europe (EU-27). First, we consider the current situation of phosphorus life cycle in Europe based on the possibility of recycling. The main limitation in using recycling as a way to meet demand for phosphorus lies in technological aspects of economic recycling of phosphorus. The recently introduced technologies, e.g. struvite fertilizers (Kabbe et al., 2015; Kabbe and Kraus, 2017), allow a potential current technical feasibility of phosphorus recycling for our system of 15 %. In this case, Table 5 shows the amount of phosphorus along the supply chain of the EU-27 member states in 2017 and Fig. 2 shows the optimal range of probability of making a rational decision on using primary or secondary sources of phosphorus based on the signals from the EU market for each country. The results show that the Netherlands uses primary and secondary sources of phospho-

Table 5
Flows of phosphorus along the supply chain of the EU-27 member states in 2017 (P Tonnes) (El Wali et al., 2019; Van Dijk et al., 2016).

Country	Import	Export	Losses	Internal production	Recycling
Austria	43315	17345	26463	77221	44997
Bulgaria	27165	11166	16324	50084	23896
Belgium	129460	62308	31990	79457	82595
Cyprus	8258	316	2656	3914	5447
Czech Republic	31679	16946	24053	77804	40311
Germany	33797	143558	164066	587217	373533
Denmark	88719	30273	29546	79810	64481
Estonia	6252	3107	4060	10032	5870
Greece	80628	6564	35025	70018	36844
Spain	446905	35162	132125	355205	295686
Finland	50671	9523	23395	38017	21125
France	484597	208940	153098	746024	421841
Hungary	48710	28111	26174	94828	36493
Ireland	67164	10604	23168	127527	104215
Italy	281988	36634	132547	299245	197155
Lithuania	15527	6156	7609	27519	14028
Luxembourg	3518	1532	952	4401	3417
Latvia	7864	3577	5616	14294	7582
Malta	1590	47	915	1063	1066
Netherlands	217313	122774	49874	122277	123785
Poland	237387	23279	95471	260514	137966
Portugal	83513	5806	28586	58355	52045
Romania	63049	10185	56781	157632	76975
Sweden	58624	18213	38720	75256	41519
Slovenia	9761	2995	6973	11326	8089
Slovakia	12098	8399	9199	30365	15999
United Kingdom	258015	43773	134553	484141	301458

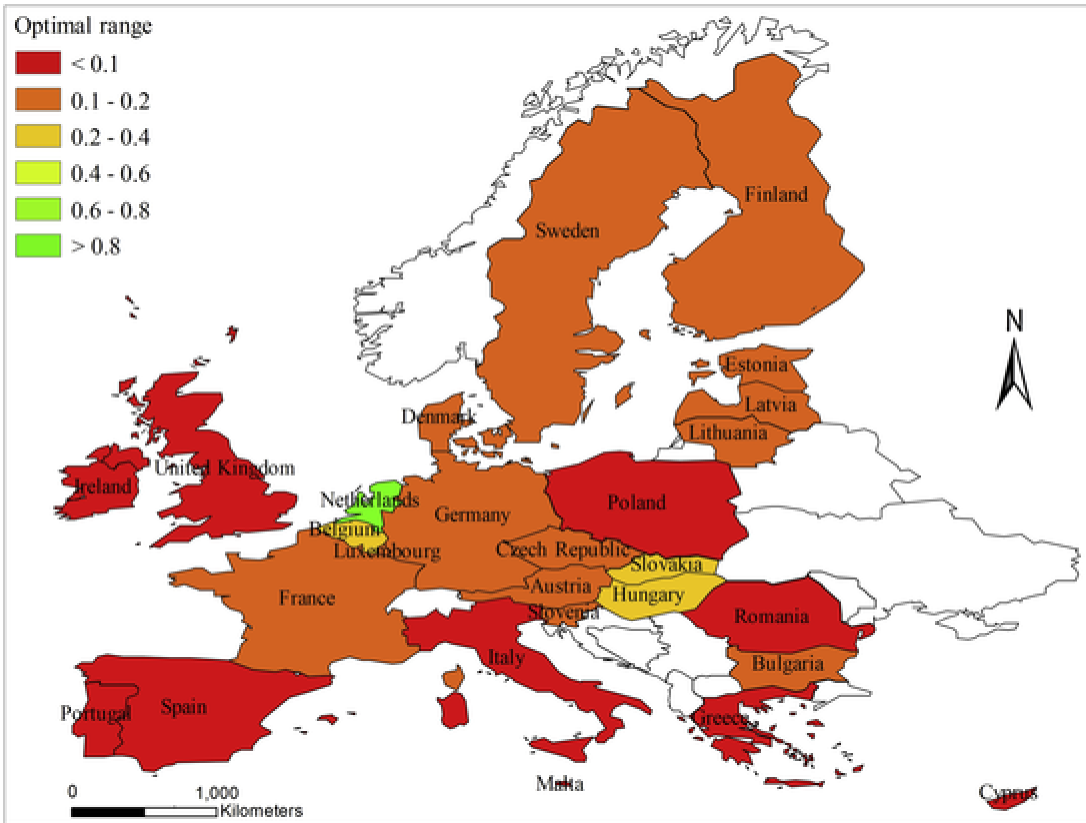

Fig. 2. Probability of making rational decision for using phosphorus primary and secondary sources based on signals (low and high deficit) for each country in the current situation.

rus based on a given signal, with probability higher than 0.8. It is followed by Belgium, Slovakia, and Hungary which remain within probability range of making a rational decision from 0.2 to 0.4. Other countries follow their strategic behavior in the current situation which leads to less than 0.2 probability of making a rational decision to supply phosphorus from both sources under the conditions of supply deficit.

Considering the conceptual overview of decision-making on the supply of phosphorus, Fig. 3 shows that all countries, with the exception of the Netherlands, prefer making a virgin material-based decision. It means they select primary sources of phosphorus supply, when the signal informs about either high or low deficit. These results shed light on the high dependency of Europe on phosphorus imports (El Wali et al., 2019).

Implementing the circular economy model is driven by the need to achieve a high level of both eco-efficiency and resource efficiency (Ma et al., 2015). It integrates economic benefits and environmental well-being into one sustainable system (Murray et al., 2017).

In line with the concept of circular economy, we consider the estimated value of phosphorus recycling will increase by up to 50 % in the next 12–15 years (Golroudbary et al., 2019; Scholz and Wellmer, 2018). Moreover, we assume that there is no difference for a decision maker to choose primary or secondary sources. Therefore, a prior belief in the case of primary and secondary sources will be 50 %. Fig. 4 shows the optimal probability range for making a rational decision when we consider the improvement of possible phosphorus economic recycling technology as a result of the adoption of the future circular economy strategy in Europe. The results show that the probability of making rational decisions based on signals will improve (by 8–16 %) for most countries such as Austria, Bulgaria, Luxembourg, the Czech Republic, Denmark, Estonia, France, Germany, Latvia, Lithuania, Slovenia, and Sweden, which will help them reach the optimum probability range of 0.2-0.4. Belgium, Slovakia, and Hungary would reach 0.4-0.6 probability of optimal range, an increase by 13–15 % compared to the current situation. On the contrary, countries such as Ireland, the United Kingdom, Portugal, Spain, Italy, Poland, Romania, Greece, Malta, and Cyprus remain at the minimum range of rational decision with probability lower than 0.1. Consequently, those countries in the minimum probability range are less circular than other countries whose probability of making a rational decision would improve in the coming 12 years.

Fig. 5 shows that all countries prefer to make a mixed sources-based decision, i.e. they choose both primary and secondary sources in response to given signals (high or low deficit).

If we assume all decision makers are members of one committee, all decisions will be virgin material-based with a fragile optimal area. Therefore, there is no Nash equilibrium in considering all 27 countries as one committee in Europe for using secondary sources of phosphorus supply based on signals from the market.

In this interpretation, there is no mixed strategy Nash equilibrium. It means that the decision makers have no motivation to adhere to their equilibrium patterns of behavior. Each decision maker is indifferent to all mixed sources-based strategies. An equilibrium strategy for a decision maker is only one of many strategies that yield the same expected payoff.

4. Conclusion

This study has considered phosphorus flows in the context of different sectors including agriculture, animal, food and non-food production, as well as human consumption. The comparative analysis of the countries in Europe (EU-27) has examined how to decide on using primary or secondary sources of phosphorus under conditions of low and high deficit.

The results show that under current circumstances all countries, with the exception of the Netherlands, prefer making virgin material-

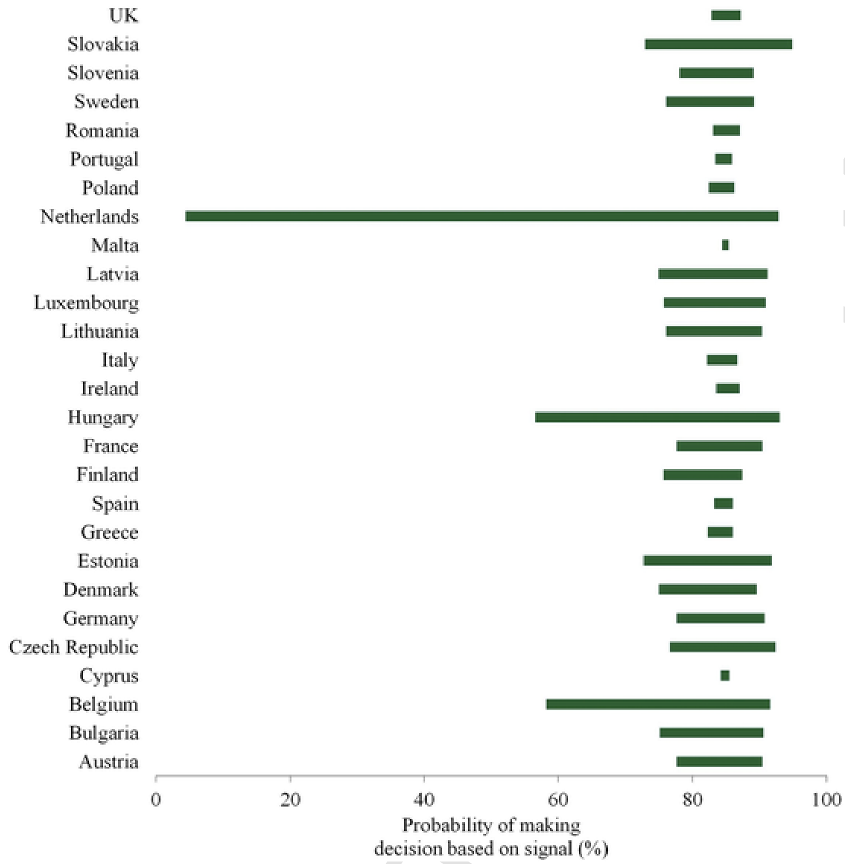

Fig. 3. Optimal range for decision on using virgin or secondary phosphorus based on signals (low and high deficit) for each country.

based decisions, when either low or high deficit is signaled. The Netherlands, with probability higher than 0.8, undertakes rational action when it comes to using both primary and secondary sources of phosphorus based on a given signal. It is followed by Belgium, Slovakia and Hungary remaining in the range of 0.2-0.4 probability of making a rational decision. Considering a potential improvement of phosphorus economic recycling up to 50 % in the 12 coming years, all countries' preferences go towards mixed sources-based decision. The probability range of making a rational decision for Belgium, Slovakia, and Hungary would be improved from 0.2-0.4 to 0.4-0.6. Moreover, an improvement would be seen for France, Luxembourg, Germany, the Czech Republic, Austria, Bulgaria, Slovenia Lithuania, Latvia, Estonia, Sweden, and Denmark, from probability range 0.1-0.2 to 0.2-0.4. On the other hand, Ireland, the United Kingdom, Portugal, Spain, Italy, Poland, Romania, Greece, Malta, and Cyprus remain at the minimum range of rational decision (probability lower than 0.1) in both situations, current and future. This analysis suggests that, those countries are less equipped or engaged for circularity than other EU countries.

This assessment of phosphorus flow carried out in accordance with the rules of circular economy shows that improvement of recycling technology will not increase the probability of making optimal rational decisions about using phosphorus sources in some countries. By analyzing the probability of making rational decisions about phosphorus recycling we have shown that the problem lies mainly with the policy of using primary or secondary sources. It seems that a precise regulatory system is needed to implement the principles of circular economy independently of the actual level of phosphorus supply. As the decisions concerning the controlling of phosphorus life cycle differ across EU-27, there is no Nash equilibrium for the recycled phosphorus in the EU. The study has also highlighted the need for an appropriate strategy that would ensure a better use of secondary sources in line with the circularity of phosphorus. New planning policies should overcome the barriers hindering the use of secondary sources of phosphorus, especially, in the countries where no improvements have been identified in decision's optimality. This paper shows that a public policy focusing on cooperation within the EU on using phosphorus recycling will efficiently address the discussed issues. Therefore, integrated approaches to support the circularity of phosphorus are strongly required.

Declaration of competing interest

The authors declare no competing financial interests.

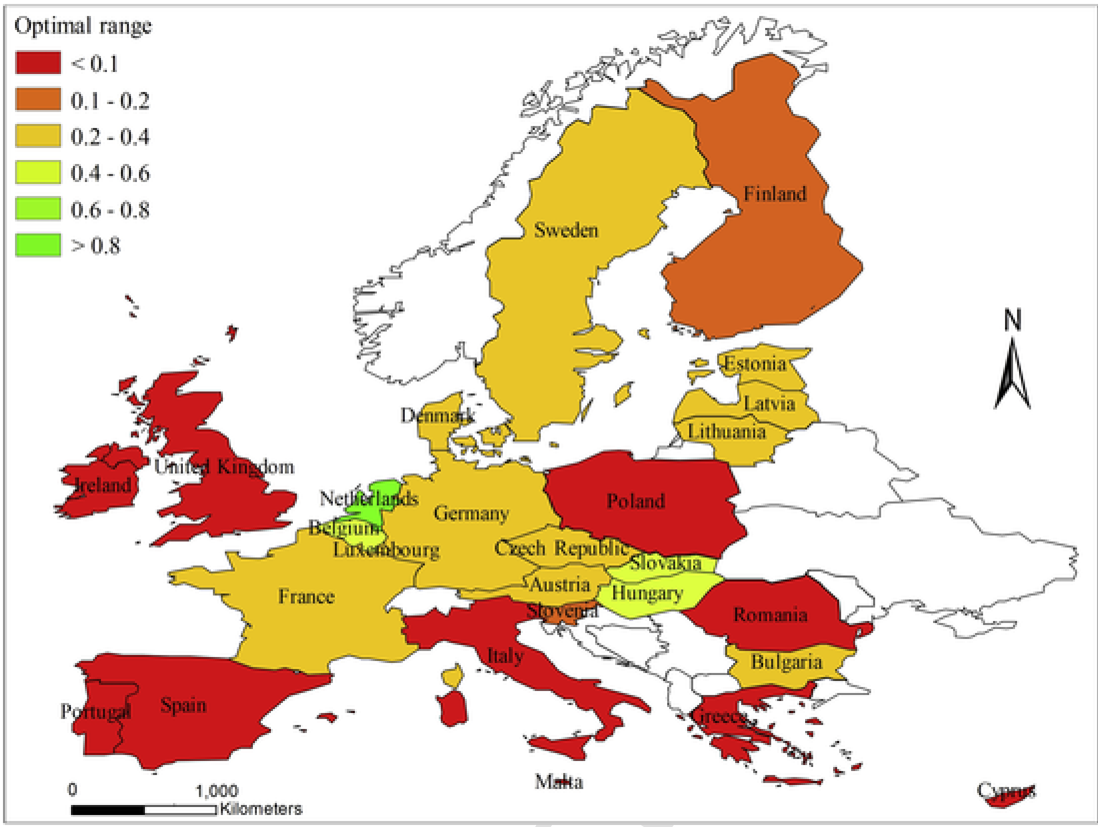

Fig. 4. Probability of making optimal decision for using phosphorus primary and secondary sources based on signals (low and high deficit) for each country in the future (12–15 years).

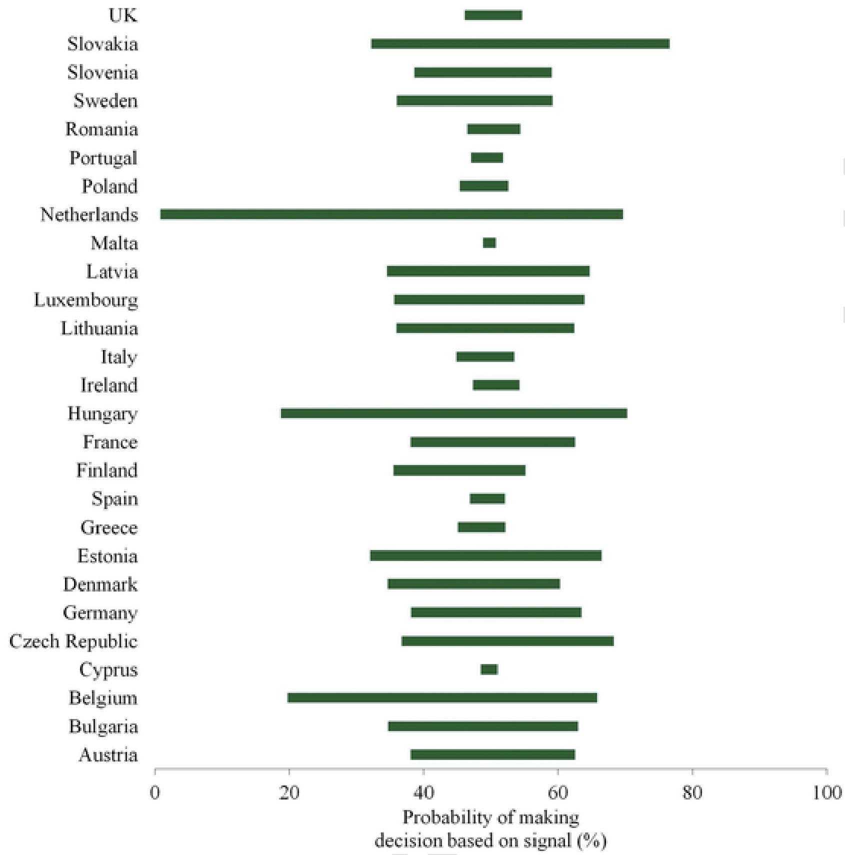

Fig. 5. Optimal range for decision on using virgin or secondary phosphorus based on signals (low and high deficit) for each country in 12–15 years.

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