The Earth’s resources and integrity are under increasing pressure from a continually expanding population (Rockström et al., 2009). Agriculture is one such pressure that underpins society through the provision of food, yet it contributes to substantial alterations in our Earth system. Global temperatures might increase by at least 1.5°C by 2100, and extremes of climate, such as precipitation or temperature events, are frequently predicted in climate change scenarios (Christensen et al., 2013). Highly variable annual and seasonal shifts in temperature and precipitation will have profound effects on agricultural function, output, and environmental impact. In particular, climate change will likely affect the patterns and efficiency of nutrient use in agricultural systems and subsequent fluxes of these nutrients to the environment. These changes are therefore critical to consider in terms of the future impact of food production systems on our environment, food security, and the resilience of food systems to climate change.

A critical nutrient for food production is phosphorus (P). Agriculture consumes vast quantities of P mined and purified from phosphate rock (quadrupled since the mid-1900s), but these P inputs are inefficiently used in the food chain and have resulted in dramatic impairment of freshwater and marine ecosystems (Elser and Bennett, 2011). Significant efforts are being made to manage eutrophication impacts, but the environmental benefits of these efforts may become increasingly difficult to predict or control under a changing climate (e.g., buffer strip function) (Ockenden et al., 2017). Management adaptations that improve the environmental performance of agriculture in the short term consequently may not be adequate in the longer term under climate change (Kates et al., 2012). Standards and targets for eutrophication control may need to be reconsidered since the sensitivity of individual catchments to climate change is inherently dependent on catchment typology and its intrinsic P buffering properties, as well as the P pressure imposed by humans (Fig. 1) (Doody et al., 2016).

**Abstract:** Phosphorus inputs to agriculture and their fate in the environment contribute to poor water quality and degradation of linked ecosystem services at great cost to society. Climate change is likely to alter the forms and timings of P fluxes from land to water and their ecological impact, the effects of which are uncertain and need to be considered to inform future catchment management for eutrophication control. The P transfer continuum is an established conceptual model that we propose as a suitable framework to consider the potential effects of climate change on catchment P transfer. Consideration of this continuum suggests that predicted changes in temperature and precipitation will likely increase P transfer and associated eutrophication costs in some regions. Further research should examine climate change effects on each tier of the continuum to inform the necessary land management adaptations and transformations to ensure future food system P efficiency and resilience.
The P transfer continuum, originally conceptualized by Haygarth et al. (2005), is a simple four-tiered model of source–mobilization–transport (or delivery)–impact that emphasizes the different scales and the interconnected dynamic nature of P mobility and mitigation in catchments (Haygarth et al., 2005; Withers and Haygarth, 2007) (Fig. 1). We propose this as a useful framework to improve conceptual understanding of the potential climate change effects on diffuse P transfer across the land–water interface and the associated eutrophication risk. We highlight some of the complex effects of national and regional variability in predicted climate change scenarios on the continuum through its potential influence on P inputs, P cycling, landscape hydrology, and eutrophication risk. A deeper understanding of these complex interactions is urgently needed to inform food system and catchment-based models to help synthesize net effects on terrestrial and aquatic ecosystems, to mitigate predicted risks to future food and water security, and to increase P efficiency.

The Phosphorus Transfer Continuum under Climate Change

**Tier 1: Sources**

*Sources* of P include direct inputs that enter through the farm gate, such as fertilizers, imported animal feed stuffs, and the application of imported livestock manure and other recycled bioresources to soil, which differ critically in amount, form, and timing depending on the agricultural system (Hale et al., 2015). Changing patterns of crop and animal production, and their yield potential due to climate change and agricultural intensification, will alter decisions on inputs because P source is intrinsically linked to crop and animal demand. Climate change will have a large, and currently uncertain, influence on regional land capability and suitability to grow specific crop types for both human and animal consumption (Lobell and Gourdji, 2012; Rosenzweig et al., 2014) and therefore, P source inputs (Jobbágy and Sala, 2014). Increased frequency of extreme temperatures in some US states are likely to cause substantial declines (63–82% highest emissions scenario) in corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) yields (Schlenker and Roberts, 2009). Conversely, increased temperatures in boreal and some temperate regions could raise agricultural output by extending or shifting growing seasons, allowing more crop choice and the possibility of double-cropping (Lobell and Gourdji, 2012), consequently altering regional P source input patterns and rates.

By 2050, meat and dairy consumption will increase significantly (Tilman and Clark (2014)). This will lead to changes in feed production and consumption, stocking densities, and the type of animals reared, affecting the amounts of livestock manure P that will need to be recycled back to the land. These changes may also be constrained by alteration
in land suitability due to climate change. Global trade and market demands will accordingly shift to reflect altered production patterns and P inputs, some countries increasing their requirements and others reducing imports (Nesme et al., 2018). Coupled with increasing urbanization and diets that are more P-intensive (Metson et al., 2012), these infrastructural changes in production and trade can be expected to greatly alter P flows though the food system (rural and urban), affecting national, regional, and catchment P budgets and thus the potential for system P inefficiency and losses. Dynamic models are therefore required to analyze the potential influence of a changing infrastructure on system P losses. To ensure P use efficiency does not deteriorate under climate change (Withers et al., 2018).

**Tier 2: Mobilization**

The *mobilization* of P includes both solubilization and detachment of P from land, of which rainfall and temperature are critical regulators. Temperature-induced changes in soil C supply will alter both biotic and abiotic soil properties, affecting P dynamics, by increasing both the mineralization of organic P and the risk of soil particle dispersion by rain splash due to reduced soil cohesion (Macleod et al., 2012). Prolonged soil drying may induce P release via the oxidation of soil organic C – Fe and Al associations but may also inhibit P mobilization by reducing P diffusion rates from soil surfaces (Sheppard and Racz, 1984). In moist environments, higher ambient temperatures will increase P diffusion and solubilization rates from soil and surface-applied soil amendments. Alternating wetting and drying will likely release soluble P through lysis of microbial cells, depending on microbial community structure and resilience to abiotic stress (Evans and Wallenstein, 2011).

Increased frequency and intensity of storm events under climate change will directly influence the mobilization of soil particles and their P signatures, depending on soil type susceptibility to particle dispersion and detachment, the amount of bare soil present, and soil P status (Sharpley et al., 2008). In temperate regions, soils may also become anaerobic during prolonged periods of wet weather, causing P release when Fe-oxides are reduced (Scalenghe et al., 2012). Greater frequency and intensity of storm events will directly affect mobilization risk from organic and inorganic amendments when freshly applied to soil (incidental P loss), especially during winter (Liu et al., 2018). This is particularly important on livestock farms where manures are recycled to land frequently and therefore more susceptible to rainfall interception (Preedy et al., 2001), especially if best-practice application periods become reduced and storage capacity is limited. A greater fundamental understanding of the effect of climate change on these different mobilization processes is required for models to operate effectively.

**Tier 3: Transport (Delivery)**

*Transport* (alternatively called *delivery*) includes the delivery of P along pathways that occur via overland flow, subsurface drainage, or leaching to groundwater. Climate change will alter pathway dominance and the speed of water routing, driven by hydrology and landscape topography, soil characteristics, and vegetation cover (Haygarth et al., 2005). For example, higher winter rainfall predicted in temperate regions may increase variable source areas of runoff in close proximity to watercourses, while more intense storms may increase the extent of infiltration excess runoff. In both cases, new critical source areas may become evident on farms where previously unseen runoff zones coincide with high soil P, or where P sources are applied, requiring more sensitive land management, the success of which may be uncertain or costly (Renkenberger et al., 2017).

Greater intensity and duration of extreme precipitation events would generate more overland flow from precipitation, leading to increased erosion, especially on hillslopes and where vegetative cover is low (Mullan, 2013). Landscape response to extreme precipitation is highly dependent on soil properties and indirectly dependent on land use and management (O’Neal et al., 2005). This places a greater emphasis on the importance of good soil management practices to optimize soil structure and infiltration capacity, such as intercropping and the development of climate extreme–resilient plant species. Conversely, regions that become drier and for longer may lose transport potential via erosion as runoff ceases or frequency declines (Mullan et al., 2012). If soils are prone to extensive cracking, however, applied P can be rapidly transported down through the soil profile as preferential flow after rain (Simard et al., 2000). Prolonged dry spells also increase top-soil compaction; the hydrophobicity of soils consequently increases the routing of flow in favor of surface runoff, leading to greater P losses especially during intense rainfall events (Shakesby et al., 2000). Our understanding of hydrology–P interactions along surface and subsurface pathways and how these may be affected by climate change is poor, requiring innovative research in real-time high frequency monitoring.

**Tier 4: Impact**

*Impact* encompasses the ecological response of lotic and lentic waterbodies to P export from point and diffuse sources and is regulated by the biological, chemical, and physical processes that govern retention (particulate P deposition, soluble P uptake by aquatic biota) and remobilization of these biotic and abiotic P stores (Jarvie et al., 2012). Under climate change, periods of low flow or complete cessations of flow that may occur in some regions will reduce the capacity for dilution, while increased ambient temperatures will accelerate nutrient cycling and biomass growth, consequently lowering dissolved oxygen concentrations, reducing the self-cleansing capacity of waterbodies and leading to increased eutrophication. Duan et al. (2012), for example, found that warming of streams entering the Chesapeake Bay consistently increased dissolved P fluxes from bottom sediments to overlying water across different land uses.

The proliferation of algae may increase as waterbodies stay warmer for longer, potentially affecting macrophyte biomass, invertebrate and fish population health, and biodiversity as more tolerant species survive (Whitehead et al., 2009). Greater precipitation in some regions will increase river flows, increasing dilution capacity where diffuse P
inputs are low, reducing P concentrations. However, in some cases, >80% of total P load can be transported from headwater catchments during high-flow events, resulting in high P loads, and poor water quality (Ockenden et al., 2016). Such high-flow events can also move P-enriched sediments to lakes and coastal areas with increased risk of hypoxia during summer months. Increased nutrient loading to subarctic and temperate lakes, for example, have been responsible for increased harmful cyanobacterial blooms since 1800 (Taranu et al., 2015); hence, if high flows increase in frequency, the ecological impact of P could move increasingly from headwaters to lakes, coastal areas, and seas.

Conclusions and Research Needs

Phosphorus cycling and transfer through landscapes is highly complex, generating variable critical source areas and time lags across catchments, which are poorly understood in terms of their ecological impacts and management response. Climate change adds to this complexity because of uncertainties in climate predictions for different regions and because every component of this complex continuum will likely be affected by climate change, leading to variable P export patterns and ecological impacts across regions and catchments. Importantly, climate change will alter the ability of regions to grow specific crops or support high animal stocking densities, as well as the length of the growing season, affecting agricultural infrastructure. Phosphorus mobilization and transport under climate change will likely increase due to increased P solubilization and detachment and quicker delivery to waterbodies. Potentially new runoff zones and critical source areas will be created in some areas, which will require transformative management.

The sensitivity of individual catchments to climate change, however, is inherently dependent on catchment buffering capacity and the anthropogenic P pressure applied (Fig. 1). Consequently, research is needed to identify catchment resilience to climate change, and the rate of change, for each tier in the P transfer continuum. Catchment buffering properties should also be investigated to establish whether they may be enhanced by management adaptations (e.g., incremental changes to capture and recover P) and transformations (e.g., entire system transformation) to reduce P fluxes and adverse ecological impacts and their associated costs. This commentary clearly identifies the need to improve modeling capability to predict climate change impacts on P processes and hydrology–P interactions in catchments, as well as the need to consider the wider impacts of agricultural infrastructure changes on P flows and efficiencies in the food system and the anthropogenic P pressures acting on catchments. In addition, we propose framing discussions on the potential implications of climate change on future P transfers by using the P transfer continuum, a simple model that can provide accessibility to knowledge for stakeholders and policymakers, as well as research direction for scientists.

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