Phosphorus Sustainability RCN Workshop Summary
January 6-10, 2014

The five-year Phosphorus Sustainability RCN intends to bring together some of the world's top scientists, engineers, and technical experts to spark an interdisciplinary synthesis of data, perspectives, and understanding about phosphorus to envision solutions for P sustainability. A key feature of the RCN is that its work will be informed by key stakeholders from relevant sectors of the global phosphorus system, including farmers and growers, food processors, fertilizer producers, waste managers, water quality managers, regulators, legislators, and others. We launched the RCN at our Kick-off Meeting May 14-16, 2013 in Washington DC. Following the Kick-off, we distributed a survey to collect further stakeholder input on the research questions developed at the kick-off. These questions were prioritized according to this feedback and consolidated by the steering committee. Four questions became the basis for the working groups at the 2014 workshop:

Group 1. Recycling: What are the most promising strategies for reduction and recovery of P flows in human, animal, and waste systems?

Group 2. Efficiency/Conservation in Production: What are the economic, social, institutional, and informational barriers and opportunities for conservation practices, adoption of new technologies, and acceptability of P efficient crops and practices?

Group 3. Demand: What are the global, regional, and country historical and forecast trends in P demand drivers? What do these trends of demand suggest about total global phosphorus demand when coupled with population growth forecasts?

Group 4. Fate, Transport, and Impact: How P is being managed on the land, how it is mobilized and transferred from a resource to a pollutant, and what can and can't be done to minimize further water quality degradation?

At the workshop, the main goals were to identify tasks within these four categories, including their associated deadlines, and to start work on those tasks. The Groups gathered as a whole at the beginning and end of each day in order to inform other groups of progress and discuss overlaps and synergies. A summary was written by each of the working groups to describe the work for the next 6 months and beyond (appendices A-D).

On the third day of the meeting, we met at the Desert Botanical Garden and held a stakeholder event at the end of the day. This provided an opportunity for local stakeholders to learn more about the issues and the project and interact with the P RCN participants. Day four of the meeting included a public Google+ Hangout On Air sponsored by the UK Consulate in Los Angeles and that can be viewed at http://www.youtube.com/watch?v=DzDQIjLavJk .

Finally, Chris Thornton, of the European Phosphorus Platform, proposed a new initiative to expand the P RCN to expand stakeholder cooperation and facilitate value-chain development and research translation for implementation of sustainable phosphorus technologies and practices in North America and especially for commercialization and propagation of P recycling approaches and technologies. This initiative, P RCN+, will begin by key RCN participants contacting P stakeholders for initial investments to support the first assessment and evaluation phase and who will together define the

objectives, scope and governance of the future “partnership”. (See Appendix E for details)

In the next stage of the RCN the working groups will continue to make progress towards their goals and deliverables described in their summaries. In August 2014, working groups will send a report of their progress to date. The Steering Committee will review the reports and provide feedback to the working groups. The next meeting will be held in Washington D.C. in May 2015 and will be attended by a subset of the current participants and will emphasize stakeholder engagement.

Please find the following appendices: A) Group 1 Summary, B) Group 2 Summary, C) Group 3 Summary, D) Group 4 Summary, E) P RCN+ proposal, F) Workshop agenda, G) Participants.

Appendix A: P Recycling – Group 1

Project Titles

Below are titles of projects Group 1 proposes. Broader summaries are in the following section. We ask RCN members to review the proposed projects to 1) offer comments on direction, and 2) volunteer to be part of projects that interest them. Please email the identified project leader or the overall group leader Bruce Rittmann (rittmann@asu.edu). The projects are organized into three themes.

Theme 1: Understanding Needs of Recovered P Users

Working Title	Output	Lead	Time
Opportunities for expanded use of biosolids and food waste	White Paper based on ongoing proposal	Larry Baker /Rob	6 months
Survey of farmer needs regarding biosolids	Survey Tool	Larry	June 2015(if funded)
Farmer needs in Indian Contexts	Popular Article and USAID proposal	Vijay	3 months

Theme 2: Technologies for P(++) Recovery and Value Added Services

Working Title	Output	Lead	Time
Meta Review of existing P recovery technologies	Review Paper	Chris Thornton	2 months
Total Value Recovery: Co-product mapping	White Paper	Bruce	1 Year
Identifying and Quantifying P from non-conventional sources and sinks	Masters Project	Vijay and John	1 year
"PhosphoSim" tool for decision makers	Funding Proposal	Dan/Dana/Larry	2019 (if funded)
Techno-economics of P recovery in developing country contexts	Journal Paper	Vijay/John	6 months
Leap-Frogging technologies for Bottom of Pyramid: Drivers for P recycling	Popular Article	Vijay/Larry	1 year

Theme 3: Policy and Management Action in Context

Working Title	Output	Lead	Time
Incidental P Management Policy Assessment	Crowd Sourced Paper/article/proposal	Brooke (interim lead)	3 month to I.D. a Lead
P cycling as Circular Economy Opportunity	Crowd Sourced Paper/Proposal	Chris (Rimjhim/Tauhid)	6 months to ID projects*
P as National Security Issue	Synthetic Paper	Dan/Dana	2 years
P Balance by Watershed or River Basin for India	Paper in addition to Group 4 Paper	Bal Krishna + Group 4	3 yrs to complete
GIS mapping of P Hotspots in USA (with analysis of opportunities and challenges)	Proposal / 3 year project if funded	Paul/Larry	1 yr for proposal

Project Summaries

Theme 1: Understanding Needs of Recovered P Users

Project 1.1: Opportunities for expanded use of biosolids and food waste.

Much of the output of P from cities is in the form of biosolids and food waste. This potential resource is largely wasted (put into sinks, such as landfills). For example, only 4% of P entering the Twin Cities is recycled. We are proposing (Feb. 2014) a study to understand how the transition from a flow-through to circular economy of P. This study, if funded, would develop a very detailed picture of flows from the regional foodshed to the Twin Cities, and the recycling of food waste and biosolids back to farmland.

Some key parts of the proposed project include: interviews and document review regarding decisions regarding biosolids disposal by Met Council; a survey of famrers regarding values and constraints of biosolids utilization; a survey of households regarding acceptability of source separation of food wastes; an analysis of potential uses of food waste; and more detailed analysis to fill in several important gaps in the P flows, with a focus on animal processing wastes.

Timeline: A proposal will be submitted to NSF in Feb. 2014; if funded, work would start in October 2014.

Products:

Summer 2014: **White paper** on opportunities and constraints for expanded biosolids use.

Late 2015: A **survey tool** to assess the potential value of biosolids, in various forms, to local farmers.

Late 2017: Project completion, with several **journal articles.**

Project 1.2: Survey of farmer needs regarding biosolids

L. Baker (lead); Rimjhim (possible collaborator on contingency evaluation questions)

Currently, about 40% of biosolids in the U.S. are utilized in agriculture. A key question is: why isn't this a higher percentage? We are focusing on one system: the MET Council's (Twin Cites) wastewater treatment system (producer) and local farmers (recipients). One part of this proposed study will be to understand the value of biosolids to farmers and the cultural, legal, and practical factors that affect the economic values. To do this, we will develop a survey tool, which would be used to query a few hundred farmers.
Because this type of survey takes considerable effort to develop, we propose sharing the survey tool with RCN researchers, who might use it for their own studies, probably adapting it as needed. The easiest way to do this would be to post in on the RCN website.
Status: We are writing a proposal to NSF now (due Feb. 20); if funded, work would start in October 2014. We would develop the survey tool in the first year (mostly in 2013) and administer it the following year (2016). We would probably be ready to post the survey tool at the end of 2015.

Project 1.3: Understanding P needs of Indian farmers, alternative P sources in the food security context

Output: Popular Article & Proposal to USAID / DFID
Lead : Vijay Chariar
Indian agriculture is largely composed of small and marginal farmers with land holdings of under 2 ha. Increasing fertilizer prices impact the economic viability of small farming resulting in farmer indebtedness and in the extreme situation farmer suicides. Eventually, this also has an adverse impact on food production and impact food security of the country. This popular article would report results from a nationwide survey of farmers and farmer cooperatives to understand alternative lower cost mechanisms for sourcing Phosphorous and other nutrient needs of farmers. The survey would also report farmer's attitudes to alternative sourcing of P and other nutrients.
Time to completion: July 2014

Theme 2: Technologies for P(++) Recovery and Value Added Services

Project 2.1: Annotated list of recent and ongoing inventories/analyses of nutrient recycling technologies

Lead: Chris Thornton, Brooke Mayer
Technologies for phosphorus recovery and recycling have been operational full-scale and producing commercially marketed products for nearly 25 years (e.g. Unitika, Japan), or much longer if P-recycling through processing of biosolids is also considered, and a wide range of technologies have been proposed and tested at different scales. These processes range from simple processes (such as using wastewater effluents to feed biomass production ponds) to extremely high-tech systems (membranes, ion exchangers, microbial fuel cells …).
Interest has accelerated significantly over the past decade as certain technologies have reached maturity (eg. struvite recovery), as pressure on agricultural use of sewage biosolids has increased, and as regulatory obligations on phosphate discharge or disposal from municipal waste water, animal manures, food waste or other industrial waste streams have been tightened and implemented particularly in Europe and North America.
Accompanying this, a number of inventories and assessments of P-recovery and recycling technologies have been published. However, most of these only address one waste stream type (eg. sewage or

digestate) or only one type of recovery route (eg. technology processes adapted to urban situations, ignoring more "appropriate" biomass-based solutions).
It is particularly emphasised by the authors that P-recovery is an area which is sadly notorious for money and effort spent in re-inventing the wheel. The archetype is struvite precipitation, where public money continues to be spent on beaker-scale, batch precipitation tests of parameters in pure chemical solutions, whereas several companies are already marketing operational processes and are operating over 20 full-scale plants in different waste streams. Similarly, despite the considerable literature showing the fertiliser value of struvite dating from the 1960's (when it was produced as a commercial fertiliser), public money continues to be spend on further "pot trials". In this case, further investigation is certainly warranted (for example into contaminants, optimisation of recovery processes, use of secondary magnesium sources, integration of the struvite process into the overall waste processing cycle, etc) but lab-scale precipitation tests are of doubtful interest.
This document therefore attempts to :

- list the inventories and analyses of P-recycling and P-recovery technologies and processes published since 2010
- also list studies which are known to be currently underway to carry out such inventories
- provide indications of which areas are covered: types of technology, waste streams …

Project 2.2: Total Value Recovery: Co-Product Mapping

Group Members: Bruce Rittmann, Mac Gifford, Brooke Mayer, Paul Westerhoff
Waste streams high in P recover potential often also include other high value products. These products include energy, precious metals, rare earth elements, other nutrients, and residuals for soil amendments. It may also include services like permit compliance, water body quality, public health, and waste handling cost reduction. We will review P recovery technologies from the standpoint of effects on and synergies with recovery of co-products. For example, oxidation of organic phosphorus to phosphate will also mobilize precious metals. We will also review effects of co-product recovery and management practices on P. For example, anaerobic digestion for methane energy recovery will also oxidize phosphate in the digestion effluent. Both of these evaluations will depend on location and scale. We hope to identify the total value of materials that contain recoverable P. We hope to map the systems dynamics of implementing various recovery or management practices on the different co-products. The aim is to make resource recovery economically viable by capturing the total value of a waste stream where it may not be for only recovering a single constituent.
Action Item: Bruce will create an outline of a journal paper next month. This will be circulated to members who will volunteer where they can each contribute.

Project 2.3: Identifying and Quantifying P from alternative, non-conventional sources and sinks of P

Masters' Students Thesis
Leads : John Mc Grath & Vijay Chariar
Review to identify potential sinks and sources of phosphorus other than those traditionally considered as such.
Potentially this will be discussed under the following three sub-headings _

- *Environmental sector* - lake sediments, marine sediments, enriched agricultural soils.

- *Waste sector* - alternative energy / alternative waste systems (from industrial sources e.g. dairy / meat rendering etc), anaerobic digestion / composting / fermentation systems.
- *Manufacturing sector* - food processing, steel industry, fly ash from incineration.

Action: Group to suggest further sources and sinks for investigation. Vijay and John McGrath to recruit student(s).
(**Time to completion : Late 2014**).

Project 2.4: PhosphoSim: An interactive decision-support simulation and visualization tool
Involved: Dan Childers, Dana Cordell, and Larry Baker

The Decision Center for a Desert City at ASU has developed a visualization-based decision-support simulation model called WaterSim that allows real-time scenario testing of a wide range of water management decisions, actions, and futures for the Phoenix AZ USA Metro Region. For nearly a decade, DCDC researchers have been using WaterSim to inform and study water management decision-making in ASU's Decision Theater, where 270° screens and 3-D visualizations engage policy-makers and water managers in scenario exercises. We will search for funding to create a similar tool for P management, and will call our decision-support simulation and visualization tool PhosphoSim. Dana Cordell and colleagues have already developed an Excel-based interactive tool that allows users to observe how decisions about individual P management parameters affect future P supply and demand curves. We will propose to expand on this novel product to allow multiple parameters to be managed at the same time, which will allow for the visualization of trade-offs, indirect linkages, and synergistic responses. We will create a highly visual front end for the model to enhance the interactive experience. We envision that it will take 4-5 years to create, test, perfect, and implement PhosphoSim once funding to do so has been secured.

Project 2.5:
Techno-economics of P recovery in developing country contexts

Project 2.6: Leapfrogging Technologies for Bottom of Pyramid
Popular Article & Proposal to Indo US S&T Forum
Leads : Vijay Chariar & Larry Baker
There have been several reports of vulnerable communities in developing countries which have experienced upward economic mobility by leapfrogging from no-connectivity to mobile connectivity. It would be interesting to explore what similar leapfrogging In the domain of sanitation and waste water technologies could achieve in terms of access to energy and nutrients. This paper will study communities in the urban slums of Delhi and generate a compilation of technologies and business models based on new zero waste technologies that could provide sanitation access alongwith revenue generation by selling energy and nutrients recovered from excrements. (Time to completion : January 2016)

Theme 3: Policy and Management Action in Context

Project 3.1: incidental P management

Inventory of policies which incidentally impact P-stewardship:
identify other policies which provide opportunities and obstacles, interactions between these policies, assessment of how these policies could better manage phosphorus (Brooke will draft)
Abstract: A number of environmental, agricultural, economic and waste policies indirectly manage Phosphorus.
For example:

- Environmental Policy
    - water quality (eutrophication)
    - water management
    - Waste Management: sewage, manure, solid waste, food waste
    - landfill policies
- Ag policies
    - soil conservation, biofuels
    - diet and food processing regulations
    - food security and food safety
    - fertilizer production (ie cadmium contamination)
- Energy Policies
    - biofuels and renewable energy
- Other
    - P users (detergents, batteries, other industries)
    - health and public safety
    - local economy movements
- other policies to be identified

This range of policy actions all direct the movement of P within a country.
We propose the creation of an inventory of policies which indirectly impact P stewardship in order to identify opportunities and obstacles, interactions between policies, and an assessment of how these policies could be better integrated, to result in more sustainable P management. We would also consider how policies are likely to change into the future, recognizing that future socio-economic drivers behind these changes do not have P in mind. For example, climate change and water scarcity may drive wider adoption of water reuse such that P cannot flow out of cities. Geopolitical contexts vary widely with regard to P stewardship, so specific regional or national case studies may be most appropriate for evaluating relevant policies, synergies and barriers.

Project 3.2: Perspectives for a circular economy for phosphorus in North America

The US Phosphorus Research Coordination Network has identified as of potential a need for R&D into implementing a local Circular Economy for phosphorus. It is proposed that this would closely involve stakeholders, in particular at local or regional levels, and would address the following issues:

- How can a circular economy be developed for phosphorus: local re-use, recovery, recycling ?

- What methodologies or processes can be used by stakeholders (authorities, civil organisations, industry) to facilitate circular P-economy, to develop business opportunities, build a phosphorus value-chain ?
- What can be learned from successful business models cases or case experience worldwide with phosphorus, or with other resources ?
- Links with local economy for other resources (use of biosolids, nitrogen, carbon)
- Potential risks of contaminants (local re-concentration)
- What are the key drivers (economic, geographical, environmental, societal) and which social and stakeholder aspects impact implementation ?
- Which regions or localities in the USA & Canada offer today particular potential for developing a Circular Economy for phosphorus ?
- What is the economic cost-effectiveness, and in particular quantify potential for sustainable job creation ?

General principles are of interest, but application to specific countries/regions should be developed, as contexts can be very different. This work could possibly be coordinated with projects being proposed in the EU/Horizon 2020 (Raw Materials Covenant for a Circular Economy)

Project 3.3: P and National Security

Involved: Dan Childers, Dana Cordell, and all other interested folks

The relationships between P sustainability and food security have been well articulated in the literature; the relationships between P sustainability and national security have not, though. Ultimately, these relationships may be summarized as national policy decisions based on real or perceived vulnerabilities to uncertainties in P supplies. We will review a number of national case studies where policies associated with P have been driven directly by national security concerns. In some cases these policies have been implemented in opaque or even secret ways while in others the policies have been quite public and bold. Examples include: 1) China's imposition of large export tariffs on mineral P, as a national security response to protecting its own P resources; 2) the quietly implemented free trade agreement between the U.S. and Morocco, as a national security response to protect its international P supply, and; 3) the secret establishment of a Committee on Phosphorus by the U.S. State department, presumably in response to the Arab Spring governmental instabilities in Northern Africa (and a national security response to possible threats to Moroccan P supplies). Key resources for our review will include the Hague Center for Strategic Studies' 2012 report on the global P rock market (http://www.hcss.nl/reports/risks-and-opportunities-in-the-global-phosphate-rock-market-robust-strategies-in-times-of-uncertainty/116/), Cordell & White's paper on global P non-governance (in press), Cordell & Neset's paper on P vulnerability (2013), and others.

Project 3.4: P Balance by Watershed or River Basin for India

There are no comprehensive document on P Balance for India. This group will try to bring such a document.

Most of the Indian soils are poor in P thus to improve and maintain farm productivity P addition is necessary. However India has no or very limited phosphorus reserve this leads to its dependence on phosphorus import. In 2010-11 India imported 7.27 million tonnes of phosphorus (P2O5) and this may be doubled in next 20 year (2030).

Phosphorus balance document may consider following assessments to estimate phosphorus balance:

A. Phosphorus out put
    a. Phosphorus requirement in terms food and agriculture.
B. Phosphorus inputs
    a. imports.
    b. Phosphorus recycling at farm level in form manure, crop residue etc.
    c. Phosphorus recycling through recycling of industrial and municipal waste.
C. Phosphorus use efficiency.
D. Phosphorus fixed in to the soil.
E. Phosphorus losses in run off & erosion.
F. Recovery of runoff phosphorus through irrigation water.

Besides these assessments we need to also estimate movement of phosphorus. If we look at data of phosphorus applied in last 60 years is a significant amount even though Indian soils have depleted in P. This indicates that either most of the phosphorus had been drained to sea or it has been concentrated to non farm areas. Another area may be to estimate amounts fixed in to the soil.
An indicative balance sheet of P in Indian agriculture published in 1989 indicates Negative balance of 4.2 million tonnes annually without considering P loss in erosion as estimates were not available.
Action item: we are looking for someone who can lead this paper. Myself and other peoples from India in the group will contribute to complete this task. This will be highly synergistic with the efforts of Group 4.

Project 3.5: GIS mapping of P Hotspots in USA

The **goal of this project** is to recognize Geographic **Hotspots** of Phosphorous Waste Generation in the USA with the aim of Identifying Locations and number of sites to focus P-Recovery Efforts.
Developed by Paul Westerhoff & Larry Baker (January 6, 2014)

Approach:

- A series of GIS layers would be developed, overlapped and analyzed to determine the nationwide location & number of P hotspots. Additional GIS layers would be analyzed to determine if there are P-demands in close proximity to P hotspots.
    - The project would/could involve some of the following
    - develop GIS layers for high density P (WWTPs, pig manure by county, etc.)
    - include WWTP information on P limits or treatment levels to estimate P levels in discharged effluent; estimate biosolids production
    - Is there a national Map of Biosolid application land area? EPA?
    - Levels of P in soil – do soil surveys exist?
    - Layers for eutrophication (nutrient impaired river stretches)
    - USGS NAQWA “P” concentration in rivers
    - Motivation for recovery is driven by “where you can put it” – GIS layer of “cropland” or managed forests, etc (land-cover analysis of all cities?)
    - Where are TMDL impacts a concern?
    - Where are there deficits of P – which would be a driver, and could they use water.
    - Look at GIS paper by Dzomback for WWTP co-located by energy cooling power generation.

- The effort would not attempt to redo TMDL or other analyses, but instead attempt to integrate aggregate spatial findings from such efforts.

Road forward – collect some preliminary GIS layers and attempt to formulate an initial brief paper and then a proposal as the goals and objectives are defined.
Timeframe: by end of summer brief paper and looking for opportunities to submit proposal.

Appendix B: Group 2 Summary

Articles:

1. A framework for enabling transformative change in sustainable phosphorus governance; Leader: Flurina; Others: JH, DC, DD, BJ

This article aims to present and discuss a conceptual and methodological framework for enabling transformative change in sustainable phosphorus governance. The framework should be applicable by different stakeholders on various scales to address concrete problems related to P sustainability. It builds on joint learning regarding the problem situation, the desired outcomes, and identification of actions through an adaptive capacity assessment.

Next steps: Refinement of the framework after February 2014, deadline for submitting the article: September 2014

2. Designing transformative change for managing legacy P; Leader: Flurina or Donnacha; Others: all

Within this article, the framework elaborated in article 1 should be applied to the case of P legacy. At the P RCN workshop we started to gather the necessary empirical knowledge through two mini-workshops embracing mainly scientists. This knowledge base will be refined through the paper writing process.

Next steps: completion of the P legacy knowledge base (especially regarding desired outcomes, indicators, objectives and later actions), after Febraury 2014, deadline for submitting the article: September 2014

3. Assessing phosphorus use efficiency techniques for low and high P legacy systems Leader: Helen; Others: HR, RM, PW,DS, JH,

Group 2, Question 1: A review of techniques to address P legacy and P deficiency in soils

Surplus phosphorus (P) generated in different farming systems is annually stored in soils and increases the amounts of total and available soil P potentially transported in land runoff with increased risk of eutrophication. The total store of P that has accumulated over time from past surpluses represents a long-term store of P or 'legacy P' that is being continually lost in runoff and could undermine efforts to restore good ecological quality in surface waters. This legacy P also represents a store of P that could be recovered by crops saving further inputs of inorganic fertiliser. In this paper we explore options to facilitate this crop recovery in addition to preventing runoff P transport. We review the techniques that would allow farmers with high P soils to bring down the P levels to a maintenance level of 10 ppm and then build up the OM in the soils so that crop plants can access P. P legacy is primarily found in developing countries, e.g. Midwestern U.S., U.K., N. Ireland.

On the other hand, in economically disadvantaged parts of the world such as sub Saharan Africa, fertilizers are not accessible by most farmers and the soils are low in P. Strategies for fertilizing crops in these areas without causing the adverse effects of agricultural fertilizer practices in the developed countries can provide an opportunity for "leapfrogging" technology. Examples of leapfrogging technologies can be seen in the jump to cell phones and in some places solar power. We review the options for low-cost, accessible P fertilizer options in developing countries with low P soils.

Methods for the review: We brainstormed overall techniques for P efficiency. Next, we chose techniques from that list that would be relevant for each context to review. We will review published literature on efficiency gains and technology adoption associated with each measure.

Proposals:

1. Application of Framework to e.g. heavy livestock production regions in Nth Ireland, Australia, Kenya, U.S. and Switzerland; PI: Donnacha/Brent; others: all

This proposal aims to apply the framework elaborated in article 1 to different P sustainability challenges.

2. Measures to draw down legacy P (safe levels of drawdown) including field studies; PI: Helen?; others: xxx
After reviewing the literature of measures to draw down legacy P, we propose to find funding to conduct field studies that will test the efficacy in the field.

3. Sustainable P management in Africa, incl. foreign investment (P fertilizers, efficiency techniques, land management, advice for contracts, small-holder farmer access); PI: Paul; others: JH, FS, DS, HR, IPNI, DDs colleague, JH

Large areas of Kenya are being bought up by foreign investors for current and future agricultural production but fertiliser practice is grossly inefficient and fertiliser prescriptions in government contracts poorly defined. There is a potential role for RCN members to (a) influence government protocols for potential investors and (b) develop sustainable P advice backed up by research activity and farmer demonstration.

Adaptive capacity survey for legacy P

Analysing P PCN results and operation of Survey Monkey
Leader: Brent; Others: all
Deadline: August 14

Appendix C: Group 3 – Global Demand Drivers

What are the global, regional, and national historical and forecast trends in P demand drivers?

Group 3 started by identifying potential outcomes and explanatory factors to provide science-based insights into micro and macro (economic and non-economic) drivers of phosphorus (P, henceforth) requirement, demand, and utilization. Two subgroups were formed. One focused on developing and estimating empirical models of spatial P demand (Global-P). The second one focused on estimating the current and future potential requirement for phosphorus associated with the production of plant- and algae-based biofuels (Biofuel-P).

Table 1 lists potential outcomes of interest. Table 2 identifies the kinds of socioeconomic, biological, ecological, and institutional factors that will be explored for the specification and estimation of the empirical models for the Table 1 variables. The choice of final models, of course, will be guided and limited by considerations such as theoretical intuition, data limitation, and statistical validation. Therefore, not all of the outcome variables identified in Table 1 are expected to be in the final studies. Similarly, some of the potential determinants identified in Table 2 may not have predictive statistical significance.

Data sources were identified from the World Bank and United Nations Food and Agriculture Organization (FAO).

The variables for both groups were organized by categories relating to potential research questions. These are shown in Table 3. Finally, the research questions were turned into individual projects. Table 4 shows working titles for these projects, with lead author, co-author participants, and tentative completion schedule.

Table 5 shows these same projects with a narrative description of the study.

The Global-P group explored available datasets and identified potential descriptive and diagnostic statistics. Multivariate polynomial regression (MPR) models were developed to correlate potential explanation variables with cross-sectional P demand. These basic results are suggestive of potential spatial and time dimensions to P demand and complex interactions and interdependence among its correlates.

The Biofuel-P group collected and analyzed literature data on terrestrial biofuel feedstock production and plant tissue phosphorus that allowed them to compute the estimated P requirements of U.S. biofuel production from seed oil biodiesel and corn bioethanol for 1980 to 2012. They then projected the P requirements for legislatively-mandated production of cellulosic advanced ethanol from woody biomass and corn stover from 2010 to 2022, based upon the most current U.S. Renewable Fuel Standards (RFS2).

The group is planning monthly teleconferences to maintain progress.

Table 1: Candidate dependent variables

DEPENDENT VARIABLES
P in food consumed in the country
P consumed by food production in the country
P imported
P exported
P storage (soil)
Fertilizer consumption
P Demand at country level
Yield Gap - country level
Yield Gap - case studies within countries
P Removal to Use Ratio - county level in USA

Table 2: Candidate independent variables

INDEPENDENT VARIABLES		
Socioeconomic Factors		**Agricultural Factors**
Population		Arable land
Population growth rate		Crop production index
Food waste		Animal production
Geopolitical variables		P in soil
Food supply		Agro-ecological zone
Food storage		Agricultural R&D
Rural/urban population		Cash crop vs subsistance
Dependency ratio		Amount of cultivated land
GDP (level and growth)		Amount of irrigated land
Income		Price of P (in time-series)
Landlocked		Agricultural wage rate
Country area		Average landholder size
Energy consumption		Agricultural commodity price index
Access to energy		Yield Gap
Male literacy rate		
Female literacy rate		**Climate:**
Total literacy rate		Avg Rainfall
GINI		Seasonal rainfall
GNI		Avg temperature
Education level		Seasonal rainfall
Female enrollment in primary education		
Investment capability		
Insurance		
Property rights		

Table 3: Scale and research question associated with variables

Dependent variables	Independent variables	Scale	Research Question
Global P demand	Population and socio-economic categories	Country or region	What do projected rates of change for the variables at the country scale affect global P demand?
Time-series of P demand	Population and socio-economic categories	Country or region	
Sensitivity of P demand	Population and socio-economic categories	Country or region	What is the sensitivity of P demand to meet consumption as a function of efficiency of animal waste P recycling, and recycling of food waste and human waste?
Sensitivity of P demand	P cycle flows	Global/national	How much P is lost through food wastage?
Sensitivity (elasticity) of P consumption	Price of P and commodities, conservation measure policies	Regional	What is the sensitivity (elasticity) of overall phosphorus consumption relative to the price of P and commodities?
Price of P	Population and socio-economic categories	Country or region	What is the market structure for P? (Collusion, strategic behavior)
Forecast P flow and demand - including non-ag uses	Economic category data - integrated P input-output table, dietary assumptions, etc.	National (Japan, India, China)	How much P is required for economic activity, directly and indirectly?
Geographic consumption patterns (esp. wrt Africa)	Price swings, location of fertilizer production capacity, market structure, regional flow of ore and fertilizer	Developing world; esp. N. Africa (exporter) vs Sub-Sahara (importers)	What is the interaction between P price and consumption in Africa (local use versus export)?
P demands of liquid transportation biofuels	Historical biomass production; congressional production mandates	Country (USA)	If we met the biofuel goals mandated by Congress, how much P is needed?
P demand of ocean CO_2 sequestration	Current data on ocean photosynthesis; NP demand needed for a nominal increase in deep carbon burial	Global	If global ocean sequestration were attempted, how much N and P would be needed per annum to halt increases in atmospheric CO_2?
P footprints and flux for biofuels and agriculture	Crop production data and fertilizer usage data	National and global	What is the P intensity for crops used for food and biofuel?

Table 4: Research projects with responsibilities and draft schedule

Task	WORKING TITLES	LEAD	PARTICIPANTS	DRAFT
1	**The effects of socioeconomic and ecological factors on P demand**	Dave Vaccari	Matsubae, Bai, Rahman, Aggarwal, Najib, Mikkelson	1-Jul-14
2	**A P-footprint Calculator**	Kazuyo Matsubae	Smith, Vaccari, Aggarwal	1-Jul-14
3	**The P requirements of US biofuels**	Val Smith	Pate, Matsubae, Cordell?	1-Jul-14
4	**The socioeconomic and ecological drivers of Yield Gap**	Rimjhim Aggarwal	Matsubae, Bai, Rahman, Vaccari, Najib, Smith, Mikkelson	1-Dec-14
5	**The P consequences of food waste**	ValSmith	Pate, Matsubae, Aggarwal, Vaccari, Bai	1-Dec-14
6	**Modeling the P consequences of dietary changes in China**	Junfei Bai	Rahman, Aggarwal, Matsubae	1-Dec-14
7	**The P demands of oceanic CO2 sequestration**	Val Smith	Pate, Vaccari, external tbd	1-Dec-14
8	**Dynamics of P removal to use ratio in the USA**	Tauhidur Rahman	Matsubae, Bai, Aggarwal, Vaccari, Najib, Smith, Mikkelson	1-Jun-15
9	**Implications of advanced biofuels on P removal to use ratio**	Nadira Najib	Matsubae, Bai, Aggarwal, Vaccari, Najib, Smith, Mikkelson, Pate	1-Dec-15

Table 5: Description of individual projects

1 **The effects of socioeconomic and ecological factors on P demand**
Dave Vaccari Matsubae, Bai, Rahman, Aggarwal, Najib, Mikkelson 1-Jul-14
This is a multivariate regression analysis that will advance the current knowledge by incorporating macro (economic and non-economic) factors affecting P demand across countries, and over time. . Such factors may l include, e.g., educational attainments, , measures of income, growth, demographic characteristics, other spatial variations, not captured by time-variant factors. .

2 **A P-footprint Calculator**
Kazuyo Matsubae Smith, Vaccari, Aggarwal 1-Jul-14
This is a web-based tool to calculate the phosphorus footprint for individual consumption from life-cycle perspective. Inputs will include individual dietary factors and virtual P costs for other consumption.

3 **The P requirements of US biofuels**
Val Smith Pate, Matsubae, Cordell? 1-Jul-14
The implications of P requirements for biofuel scale-up in the USA will be computed based

stoichiometry and production rates of the biological feedstocks, including both first generation and advanced biofuels.

4 **The socioeconomic and ecological drivers of Yield Gap**
Rimjhim Aggarwal Matsubae, Bai, Rahman, Vaccari, Najib, Smith, Mikkelson 1-Dec-14
This is a nonlinear multivariate regression analysis that will advance the current knowledge by incorporating socioeconomic parameters as factors affecting Yield Gap at the country level. Inputs will include, e.g., literacy measures, economic growth rates, population density and growth rates, regional factors, etc.

5 **The P consequences of food waste**
Val Smith Pate, Matsubae, Aggarwal, Vaccari, Bai, Rahman 1-Dec-14
Changes in the global demand for food are responsible for major increases in P mining and human consumption. We will assess the contribution of food waste to global P demand, building upon a 2013 streamlined life cycle assessment for nitrogen emissions related to food waste.

6 **Modeling the P consequences of dietary changes in China**
Junfei Bai Rahman, Aggarwal, Matsubae 1-Dec-14
Dietary patterns in China and Japan are believed to affect P demand both inside and outside those countries. This is to analyze how socioeconomic factors will affect P demand through dietary changes.

7 **The P demands of oceanic CO2 sequestration**
Val Smith Pate, Vaccari, external tbd 1-Dec-14
Fertilization of the world's oceans has been proposed as a geoengineering solution to increasing atmospheric CO2 and global warming. This analysis will seek to quantify the magnitude and implications of the P demand of this proposed effort.

8 **Dynamics of P removal to use ratio in the USA** Tauhid Rahman
Matsubae, Bai, Aggarwal, Vaccari, Najib, Smith, Mikkelson 1-Jun-15
Develop and estimate econometric models of P-removal-to-use-ratio incorporating dyanmic, cross-sectional and spacial interdependence. The work will be done at the county level for the USA.

9 **Implications of advanced biofuels on P removal to use ratio** Nadira Najib
Matsubae, Bai, Aggarwal, Vaccari, Najib, Smith, Mikkelson, Pate 1-Dec-15
Building on the work done in task 8, we will assess the implications of future advanced biofuels development on P removal to use ratio in the USA.

Appendix D: Group 4 Summary

The legacy P in catchments gang

Product 1: EST viewpoint article
Working Title:
Historical perspectives and dynamics of legacy P in global catchments

Objective:
- Communicate the importance of accessing the long-term temporal dynamics of P legacy in global catchments and the implication of the legacy for P sustainability.
- Convey the long-term trajectories of P accumulation and export to assess and quantify legacy P at the watershed scale (for rivers of the globe).
- Report preliminary analyses for Yangtze, Thames, and Maumee

Leader: Powers
Participants: Shen, Chan, Jarvie, Elser, Sharpley, Haygarth, Peterson

Timeline: 1 March 2014

Product 2a: Proposal to MN Dept of Agriculture
Objective: Prepare proposal to obtain funding to support PD/grad student effort to develop detailed P legacy framework methodology for US catchments.

Leader: Powers
Participants: Elser, Sharpley, socioeconomics partner?

Timeline: 31 January deadline. Project start date: July 2015.

Product 2b: Proposal to UK NERC
Objective: Prepare proposal to obtain funding to support PD/grad student efforts to develop detailed P legacy analysis for UK catchments.

Leader: Haygarth
Participants: Jarvie, Sharpley

Timeline: January 2015 target

Product 2c: Proposal to China NSFC
Objective: Prepare proposal to obtain large-scale funding to support postdoc/grad student efforts and international collaboration to develop detailed P legacy analyses for multiple global catchments, including soil pools.

Leader: Shen
Participants: Jarvie, Sharpley, Elser, Powers, Haygarth, Peterson, Chan

Timeline: March 2015 target

Product 3: Conceptual article about P legacy
Objective: Conceptualize and quantify the magnitude, typology, and spatial distribution of legacy P pools in catchments.

Leader: Jarvie
Participants: Peterson, Powers, Sharpley, Haygarth

Timeline: outline in 6 months, completion in January 2015.

Product 4: Legacy P extension communication
Objective: Summarize and communicate issue of legacy P to appropriate stakeholders (farmers, water managers) via flier/pamphlet and associated media, working through appropriate extension offices.

Leader: Peterson
Participants: Powers, Sharpley, Jarvie, Haygarth, Shen

Timeline: June 2014

Appendix E: P RCN+: Towards a North America partnership for phosphorus sustainability?

First steps taken to organize stakeholder cooperation and facilitate value-chain development for sustainable phosphorus management in North America.

At the 2nd P-RCN meeting key stakeholders present identified the need to go beyond the coordination of research and to establish a North America "partnership" to actively develop sustainable phosphorus management and the business value chain. The development of such a "partnership" is seen as one long-term outcome of the 5-year P-RCN project. The operational form of the "partnership" remains to be defined (network, structure, cooperation platform …), probably with regional implementation in different zones of the USA and Canada. Motivated RCN participants are now contacting frontrunner companies and organisations to launch a pre-launch phase of stakeholder contact, project definition, feasibility and funding, initially coordinated by the P-RCN Steering Committee.

Interested companies and structures should contact Jim Elser, Arizona State University, P-RCN lead investigator j.elser@asu.edu

The P-RCN (Phosphorus Research Coordination Network) has research objectives only, and does not have a remit or resources to develop operational phosphorus value chain actions or business facilitation. The North America sustainable phosphorus "partnership" project is therefore independent of P-RCN, although it is being initially taken forward by several P-RCN participants. The project will address similar objectives to P-RCN, but from an operational business and stakeholder perspective, including implementation-oriented R&D.

The "partnership" may best be structured regionally because phosphorus management issues are variable in different parts of the continent (e.g. regional livestock manure surpluses, water quality issues, urban structure, biofuels development, industry …). It is noted that it may not be appropriate to create a new (legal) structure: hosting within an existing body may be more efficient in terms of operating cost and administrative simplification.

The project will benefit from the experience of the European Sustainable Phosphorus Platform and the Japan Phosphorus Recycling Council, both of whom participated at the second P-RCN meeting, January 2014, Arizona.

The objectives of the proposed North America sustainable phosphorus "partnership", to be refined and reviewed with the initial participants, could include:

- Networking between operators and stakeholders concerned by phosphorus management in different sectors
- Make business chain contacts to facilitate implementation of viable, innovative activities and operational partnerships
- Directory of resources: competences, products, phosphorus flows, technology suppliers, R&D and implementation expertise
- Technology monitoring, including feasibility assessment, inventory of suppliers, cost/benefits, LCA …
- Regulatory information and proposals, necessary to accompany management of phosphorus, including waste, environmental, discharge, agricultural aspects
- Outreach / awareness raising / targeted communications

- Ensure representation of US and Canada phosphorus management stakeholders and frontrunners in international meetings and initiatives
- Prepare operational projects/tenders in order to obtain funding for research, demonstration projects, integration and dissemination, where identified as useful

Setting up a North America Sustainable Phosphorus Partnership

Business sectors and organisations that may be motivated to join the "partnership" include those concerning fertilisers, soil amendments, composting and anaerobic digestion, biochars, phosphate mining, solid waste management, wastewater, technology suppliers and engineering consultants (nutrient recycling, P-removal …), agricultural and related sectors (livestock production, phytase, seeds, animal feeds, …), biofuels, cities / states / counties, utilities, agencies / funding programmes and knowledge institutes' technology transfer sections.

The first stage proposed would bring together a small group of frontrunner companies and organisations (businesses and operators, industry sectors, water and waste utilities/regional authorities) willing to fund a first establishment and evaluation phase, and who will together define the objectives, scope and governance of the "partnership".

The proposed calendar is to identify these frontrunners over coming months, then (with these initial participants) to put in place dedicated human resources to define and develop the project, possibly leading to a launch meeting in parallel to the 3rd P-RCN meeting in Washington DC, May 2015 (to be decided by the initial participants).

Contact: j.elser@asu.edu

Appendix F: Phosphorus Sustainability RCN Workshop Agenda
January 6-10, 2014
Arizona State University, Wrigley Hall 481

Monday, January 6
Location: Wrigley Hall 481

9:00 – Welcome to ASU Global Institute of Sustainability – Rob Melnick (Chief Operating Officer, GIOS)
9:15-9:45 Bioenergy & Nutrient Recovery Strategies in Agriculture – Anthony Michaels, Proteus Environmental Technologies
9:45 – Overview of Phosphorus Sustainability RCN – Jim Elser
10:00 – Working group presentations (Group leaders introduce group members and describe focal questions, meeting goals, and 6-month deliverables.). Groups 1 (Rittmann) and 2 (Cordell)
10:30 Break
11:00 Groups 3 (Vaccari) and 4 (Sharpley).

12:00 Buffet Lunch outside Wrigley 481

12:30 – PEER research project activity report – Vijay Chariar
1:00 – Overlap and synergies discussion: What are potential areas of overlap? How will groups work together or divide tasks?
1:30 - Working group meetings (breakout) - Create detailed To Do list/agenda for the meeting to achieve meeting goals (rooms: WRIG 481 (seats 60), WRIG 308 (seat 10), and WRIG 323 (seats 20); SHESC room 350B.
4:30: Groups report back on progress. WRIG 481

Tuesday, January 7

9:00 - 9:30 Announcements and group plans for the day. WRIG 481
9:30 – Break out into working groups (same rooms as above)

12:00 Lunch: Box lunch available outside WRIG 481

4:30: Groups report back on progress. WRIG 481

Wednesday, January 8
Location: Desert Botanical Garden, Volunteer Headquarters

8:30 meet in hotel lobby to leave to DBG
9:00 - 9:30 Announcements and group plans for the day.
9:30 – Break out into working groups (rooms: Volunteer Headquarters, Wells Fargo Classrooms A and B)

12:00 Lunch: Boxed lunch available main room

3:30 – 4:30 Mid-point presentation and discussions from each group (reports on progress and agenda) (15 min each)
4:30 Stakeholder session – Introduction of P sustainability RCN – Jim Elser

5:00 – Happy hour at Gertrude's followed by dinner

Thursday, January 9

9:00 - 9:30 Announcements and group plans for the day. WRIG 481
9:30 – Break out into working groups (rooms WRIG 481 (seats 60), WRIG 308 (seat 10), WRIG 323 (seats 20), SHESC room 350B.
{9:15 - set up for British Consulate Google+ Hangout
10:00 - Google+ Public Hangout (just involves ~3-4 RCN members) }

12:00 Lunch: Box lunch available outside Wrig 481

4:30 Groups report back on progress. Wrig 481

Friday, January 10

9-10:30 Groups plan activities and benchmarks for next 6 months. (Breakout: rooms WRIG 481 (seats 60), WRIG 308 (seat 10), WRIG 323 (seats 20), SHESC room 350B.

10:30 break

11:00 - 12:00 Group reports on progress and plans for next 6 months WRIG 481

12:00 Buffett LUNCH; final thoughts and instructions (Jim Elser) WRIG 481

2 - 4:00 Optional Tour of the Tres Rios constructed treatment wetlands (capacity 12; meet outside entry of Wrigley bldg. at 1:15. Sign up with Jared!
http://phoenix.gov/waterservices/tresrios/wetlandproject/index.html)

Adios and Save The P(ee)!

Appendix G: Workshop and Stakeholder Event Participants with Affiliations

Table 1: Workshop Participants and Affiliations

WG#	Core members	Affilliation
1	Dan Childers	Arizona State University
1	Jared Stoltzfus	Arizona State University
1	Mac Gifford	Arizona State University
1	Bruce Rittmann*	Arizona State University
1	Paul Westerhoff	Arizona State University
1	Vijayaraghavan M Chariar	Indian Institute of Technology, Delhi
1	Lawrence A. Baker	Water Resources Center, U. Minnesota
1	Zhengyi Hu	Graduate University of Chinese Academy of Sciences
1	Balkrishna Yadav	Jain Irrigation, Inc
1	Brooke Mayer	Marquette University
1	Hisao Ohtake	Osaka University
1	Chris Thornton	Phosphorus Platform
2	Helen Rowe	Arizona State University
2	Flurina Schneider	Arizona State University
2	Jennifer Hodbod	Arizona State University
2	Dana Cordell*	Inst. for Sustainable Futures U. of Tech., Sydney
2	Jeff Holiman	Public Hygiene Lets Us Stay Human
2	Donnacha Doody	Agri-Food & Biosciences Institute, Ireland
2	Paul Withers	Bangor University
2	Brent Jacobs	Institute for Sustainable Futures, Australia
2	Rob Mikkelsen	International Plant Nutrition Inst.
2	Dr. Soman	Jain Irrigation, Inc
3	Rimjhim Aggarwal	Arizona State University
3	Tauhid Rahman	University of Arizona
3	Junfei Bai	China Agricultural University
3	Val Smith	Dept. of Ecology and Evolutionary Biology, U. Kansas
3	David A. Vaccari*	Stevens Insitute of Technology
3	Nadira Najib	Stevens Insitute of Technology
3	Ron Pate	Sandia National Laboratories
3	Kazuyo Matusbe	Tohoku University
4	Neng Iong Chan	Arizona State University
4	Jim Elser	Arizona State University

4	Roberto Gaxiola	Arizona State University	
4	Andrew Sharpley*	Dept. of Crop, Soil and Environ. Sciences, U. Arkansas	
4	Heidi Peterson	Water Resources Center, U. Minnesota	
4	Helen Jarvie	Natural Environment Research Council, UK	
4	Jianbo Shen	China Agricultural University	
4	John McGrath	Queen's Univeristy of Belfast	
4	Phil Haygarth	Lancaster University, UK	
4	Steve Powers	University of Notre Dame	
Invited speaker		Anthony F. Michaels	Proteus Environmental Technologies

*Indicates group leader

Table 2: Stakeholder Event Attendees and Affiliations

Name	**Affiliation**
Bill Petuskey	OKED, Arizona State University
Mark Henderson	Global Resolve. ASU
Tom Crawford	Bio Huma Netics
Gary Peterson	Urban Farm
Patty Emmert	Slow Food
Andy Physioc,	Bella Fresh Produce
Julie Murphree	Farm Bureau
Bryan McLaren	Waste Management, Inc
Sally Mouakkad	British Consulate
Karl Wyant	Arizona State University
Jessica Corman	Arizona State University
Tom Walz	Tres Rios