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Bottom-up adaptive management and stakeholder participation for clean water and healthy soils in a complex social-ecological system

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BOTTOM-UP ADAPTIVE MANAGEMENT AND STAKEHOLDER PARTICIPATION FOR CLEAN WATER AND HEALTHY SOILS IN A COMPLEX SOCIAL-ECOLOGICAL SYSTEM

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Abstract

Protection of water resources in a changing climate depends on bottom-up stewardship and adaptive management. From the ground up, a vital component is maintaining soil ecosystem services that regulate water, recycle nutrients, sequester carbon, provide food, and other benefits. Interacting spatial, social, and physical factors determine agricultural and stormwater management, and their impact on water. This dissertation explores these dimensions within a complex social-ecological system. The first chapter evaluates a participatory process to elicit solutions to complex environmental problems across science, policy, and practice. The second chapter studies on-farm soil assessment and its role in informing management decisions and supporting adaptive capacity. The third chapter investigates cross-scale dynamics of residential green stormwater infrastructure (GSI) for improved water resource management in a broader social-ecological context.

Integrating participant feedback into current science, research, and decision-making processes is an important challenge. A novel approach that combines a Delphi method with contemporary "crowdsourcing" to address water pollution in Lake Champlain Basin in the context of climate change is presented. Fifty-three participants proposed and commented on adaptive solutions in an online Delphi that occurred over a six-week period during the Spring of 2014. In a follow-up Multi-Stakeholder workshop, thirty-eight stakeholders participated in refining and synthesizing the forum's results. The stakeholders' interventions from the crowdsourcing forum have contributed to the current policy dialogue in Vermont to address phosphorus loading to Lake Champlain. This stakeholder approach strengthens traditional modeling scenario development to include priorities that have been collectively refined and vetted.

Healthy agricultural soils cannot easily be prescribed to farms and require knowledge and a long-term commitment to a holistic and adaptive approach. The second chapter addresses the questions: "to what extent do farmers use indicators of soil health, and does feedback inform management decisions?" A survey of farmers in two Vermont watersheds was conducted in 2016 showed relatively high use of fourteen soil indicators and high rankings of their importance. The finding that there were differences in use and perceived importance of soil indicators across management and land-use types has implications beyond the farm scale for agriculture, and the provision of ecosystem services. Soil management relates to broader adaptation strategies including resistance, resilience, and transformation that affects adaptive capacity of agroecosystems.

Bottom-up adoption of environmental behaviors, such as implementing residential GSI, need to be understood in the context of the broader social-ecological landscape to understand implications for improved water management. A statewide survey of Vermont residents paired a cross-scale and spatial analysis to evaluate how intention to adopt three different GSI practices (infiltration trenches, diversion of roof runoff, and rain gardens) varies with barriers to adoption and household attributes across varying stormwater contexts from the household to watershed scale. Improved stormwater management outcomes at the watershed and local levels depend on management strategies that can be implemented and adapted along the rural-urban gradient, across the bio-physical landscape, and according to varying norms and institutional arrangements.

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Dedication

This dissertation is dedicated to my daughter, Maya Faye Edson, and her dad too, Daniel Archer Edson.

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1 Introduction

Environmental protection and a sustainable water resource future depends on valuing dynamic, bottom-up, adaptive management and social learning processes to inform science, policy, and practice (Klenk et al., 2015; Pahl-Wostl, 2009). This dissertation explores bottom-up dimensions of adaptive capacity in complex social ecological systems. The first research chapter evaluates a participatory process to elicit solutions to complex environmental problems across science, policy, and practice. The second chapter studies on-farm assessment and its role in informing management decisions and supporting adaptive capacity. The third research chapter investigates cross-scale dynamics of residential GSI for improved water resource management in its broader social ecological context.

This introductory chapter reviews a wide literature base to support this dissertation's research. First, to provide a broader context, the "wicked problem" (Rittel and Webber, 1973) of eutrophication and its sources are described as well as social and ecological dimensions that make nutrient management challenging. This provides the rationale for the explorations of participatory process and adaptive management that follow. Participatory and adaptive management processes are needed to manage cross-scale dynamics and challenges of "fit" in complex social-ecological systems. Environmental behavior can be assessed within this context of social-ecological fit. Next, dimensions of adaptation are described with a focused discussion on multifunctional attributes of soil health and green stormwater infrastructure as they relate to broader water pollution, and sustainability challenges. Finally, this introductory chapter presents a synopsis of policy and environmental conditions in Vermont and Lake Champlain as it relates to pollution from agricultural and developed landscapes and concludes with a brief background on each of the research chapters included in this dissertation.

1.1 Water resources and the wicked problem of eutrophication.

The threat to human and ecosystem health from altered hydrology and water pollution is on the rise globally (Carpenter et al., 2011; WWAP, 2009). In the United States, 53% of the assessed rivers and streams; 70% of assessed lakes, reservoirs and ponds; and 79% of the assessed bays and estuaries are impaired for meeting “designated uses” including supporting drinking water supply, supporting aquatic life, and recreation (US EPA, n.d.). Water body impacts associated with point and nonpoint source pollution, modified hydrology, and habitat alteration are well-documented (OARM US EPA, n.d.; Wear et al., 1998; Wemple et al., 2017). Eutrophication, attributed mainly to high phosphorus and nitrogen loads, is one of the most ubiquitous water quality problems impacting surface freshwater resources in the United States and throughout the world (US EPA, 2016; WWAP, 2009). High nutrient loads can cause harmful algal blooms, and decreased dissolved oxygen in freshwater and coastal systems (Diaz et al., 2014; Dodds et al., 2009). This in turn can cause significant human health risks, economic losses, and declines in fisheries and ecosystem health (Conley et al., 2009; Dodds et al., 2009; Kotak et al., 1993; WWAP, 2009).

Eutrophication from nutrient loading is largely attributed to agriculture and development (Thornton et al., 2013; Patterson et al., 2013; Carpenter et al., 1998; Sharpley et al., 2001; Arnold & Gibbons, 1996). Some sources of phosphorus pollution are easier to target and manage than others but likely involve costly investments in technological and infrastructural fixes (Sharpley et al., 2001). For example, in the United States, upgrades of sewage treatment plants have allowed point source reductions of nutrient loading but does not completely solve the problem. The persistence of algae blooms and nutrient pollution show the need to target reduction from more diffuse sources of pollution emanating from agricultural and developed landscapes (Conley et al., 2009; Patterson et al., 2013; Sharpley et al., 2001). In agriculture, runoff of sediments, nutrients, and pesticides are major sources of non-point source water pollution (Carpenter et al., 1998; Dowd et al., 2008). Many argue that mitigating environmental impacts and sustaining agriculture fundamentally depends on supporting healthy soils that slow erosion, filter and store water, sequester carbon, and mediate nutrient cycling (Amundson et al., 2015; Banwart, 2011; Doran, 2002). These functions of soil are missing where soils are paved over (Banwart, 2011). In more developed settings, ineffective stormwater management can cause increases in runoff rates and volumes, downstream flooding, stream bank erosion, increased turbidity, habitat loss, sewage spills, infrastructure damage, and transport of pollutants that contaminate receiving waters (Arnold Jr and Gibbons, 1996; UNEP, 2014; OARM US EPA, n.d.).

Both social and physical dynamics influence runoff and pollution in agriculture and developed landscapes (Ahiablame et al., 2013; Patterson et al., 2013; Pfeifer and Bennett, 2011; Wright et al., 2016; Zhang et al., 2015). For example, previous research of residential stormwater pollution includes linkages to social indicators including residential lawn fertilization, higher home values, household income, and informal and formal neighborhood norms (Fraser et al., 2013; Pfeifer and Bennett, 2011). Legacies of existing infrastructure, values, and governance systems creates ambiguity around its effectiveness in reducing pollution (Ostrom, 1990; 2005; Osherenko, 2013; Patterson et al., 2013; Ekstrom & Young, 2009; Pahl-Wostl, 2009).Interactions between decision making, land use, nutrient transport, eutrophication, and climate change is characterized by uncertainty including unpredictability, incomplete knowledge and ambiguity (van den Hoek et al., 2014) making a wicked problem that is not easily defined or solved (Rittel and Webber, 1973; Patterson et al., 2013).

1.2 Adaptive management and bottom-up learning

The need for adaptive management (Holling, 1978), or "learning to manage by managing to learn" (Bormann et al., 1994, p. 1) in science, policy, and practice is well established. (Pahl-Wostl et al., 2007). Scientific models that are employed to attribute nutrient loading values to point and non-point sources are based on estimates of complex interdependent climatic, hydrological and biogeochemical interactions that are constrained by data and knowledge limitations (Couture et al., 2014; Fowler et al., 2007; Isles et al., 2015). Models of social dynamics and human behaviors face similar constraints. The legitimacy and effectiveness of model outputs for informing decision making are further constrained in that they often do not account for the dynamic, uncertain, and interdependent governance contexts of social-ecological systems (Bäckstrand, 2003; Folke et al., 2005; Pahl-Wostl, 2009; Patterson et al., 2013). In addition, lag effects of management efforts and underlying physical processes can occur at medium, long term, and even geological time scales (Meals et al., 2010; Sharpley et al., 2001). Models integrating scientific knowledge can be used to carefully select adaptive management experiments to fill in knowledge gaps about complex interactions across scales (Walters, 1997). But Walters (1997) points to four main barriers to implementing experimental adaptive management plans in real life. These barriers include reliable model output assessments of policies to be tested, risks of large-scale management experiments, self-interest in research and management organizations, and ecological value conflicts (Walters, 1997).

At the same time innovative management approaches are needed to capitalize on self-organizing properties of the complex systems to be managed (Pahl-Wostl et al., 2007). Armitage et al., (2009) articulate the need for adaptive co-management involving more exchange between collaborative approaches and adaptive management frameworks to support learning across scales. In comparing "prediction-and control regimes" to "integrated adaptive regimes" for water resource management, Pahl-Wostl et al. (2007b) describe more horizontal governance, policy integration, multiple scales of analysis, shared information, decentralized infrastructure, and diversified financial resources. In this context of transitioning to a new paradigm, social learning that increases awareness of complex biophysical and social systems is essential to navigate new territory (Pahl-Wostl et al., 2007). "Learning through complexity" (Armitage et al., 2009) requires technical expertise and local traditional knowledge, both experiential and experimental strategies for feedback, diversity, and cross-scale exchange. Monitoring and assessment is an essential tool to support learning across scales, and over time, and to facilitate adaptive management (Armitage et al., 2009). Building on the idea that learning exchanges are needed across scales, research by Danielsen et al., (2010) found differences in scale and rate of implementation between local and scientist-expert level assessment. Local participation in monitoring informed responses for natural resource management at much shorter implementation periods than scientist executed monitoring where influence occurs mostly at regional, and national scales and over longer time periods (Danielsen et al., 2010).

1.3 Stakeholder participation

The need for stakeholder involvement in socio-ecological problem solving is demonstrated by the gap between scientific knowledge and the generation of useful adaptation information to inform decision makers (Bradshaw and Borchers, 2000; Fowler et al., 2007; Pahl-Wostl et al., 2007). Without stakeholder engagement, scientific models can present solution sets that obscures ambiguity and tradeoffs, and oversimplify existing knowledge and experience (MacMillan and Marshall, 2006; Susskind, 2013; Zia et al., 2011). Management approaches to designing flexible adaptive solutions must be inclusive of multiple viewpoints (van den Hoek et al., 2014). In addition to unpredictability and incomplete knowledge, uncertainty from multiple valid and conflicting problem frames requires an approach that can resolve ambiguity to improve understanding of complex problems and design of solutions (Brugnach et al., 2011).

Given this complexity, Miller et al. (2008) point to the value of epistemological pluralism within an adaptive management approach that values multiple ways of knowing. The generation of information from experts and stakeholders who have first-hand experience, for example, with water resource systems, can add value to policy discussions (Susskind, 2013). Stakeholder processes are needed to manage uncertainty, adaptively define problems, and expand the set of solutions that can be considered for multiple end-users in research, policy, and practice (Dietz et al., 2003; Fazey et al., 2014; Patterson et al., 2013; Van der Brugge and Van Raak, 2007). When there is no single right or wrong answer in translating science to management, stakeholders can contribute critical input (Bäckstrand, 2003; Clayton, 1997; Moore et al., 2009).

The contribution of stakeholder participation to scientific inquiry is an important strategy in promoting an adaptive management approach in policy and practice, and examining alternative stable states and scenarios (Klenk et al., 2015; Peterson et al., 1997). Although the need for increased participation in the generation of solutions is well-established, integrating participant feedback into current science, research, and decision-making processes is challenging (Fazey et al., 2014; Klenk et al., 2015; Reed, 2008). High levels of complexity and uncertainty require diverse knowledge and values of multiple stakeholders across scientific and other communities of practice (Folke et al., 2005; Ostrom, 2009; Patterson et al., 2013). Participatory processes that integrate explicit and tacit knowledge can add legitimacy and accountability in instances when science occurs amid ambiguous political, social, environmental, and economic values (Bäckstrand, 2003; Norton and Steinemann, 2001; van den Hoek et al., 2014)

1.4 Transboundary issues and social-ecological "fit"

Effective water resource management must balance tradeoffs to include functional spatial fit within hydrological boundaries, a dynamic fit to adapt to climate change, and a social fit to manage political and economic dimensions (Herrfahrdt-Pähle, 2014). Reducing nutrient pollution from agriculture and development requires strategies that can satisfy varied motivations and goals across local and regional management scales (Patterson et al., 2013) and address governance mismatch between administrative, policy, and biophysical boundaries (Porzecanski et al., 2012; Pahl-Wostl, 2009). Cash et al. (2006) present a schematic of different scales and levels involved in human-environment dynamics, providing a useful model to illustrate the multiple cross-scale factors that are critical to sustainable stormwater management. While watershed delineations are useful for hydrologic and water quality analysis, governance and coordinated implementation at the watershed scale faces technical, institutional, and perceptual barriers including uncertainty around effectiveness, insufficient capacity, and fragmentation of multi-jurisdictional efforts (Baptiste et al., 2015; Cohen and Davidson, 2011; Roy et al., 2008).

Griffin (1999) defines a "problem-shed" as a geographic area that is large enough to encompass the issues but small enough to make implementation of solutions feasible. Cohen and Davidson (2011) raise the question if the watershed unit, originally a technical delineation, is an appropriate scale for governance. At the watershed scale, they point to challenges of accountability, public participation and asymmetries with the boundaries of "problem-sheds" and add the image of a '"policy-shed" as a geographic area over which a governmental entity has legislative authority such as a nation, state, province, county or municipality (Cohen and Davidson, p. 5, 2011). In a complex transboundary governance system, actors operate in different arenas and scales, employing a variety of tools and strategies with varying degrees of collaboration and coordination (Koliba et al., 2010, 2016; Osherenko, 2013; Scheinert et al., 2015). Despite useful frameworks and potentially practical management contexts provided by spatial, hydrological, and political, boundaries, water governance problems are fundamentally transboundary (Cash et al., 2006; Cohen and Davidson, 2011; Moss and Newig, 2010; Susskind and Islam, 2012).

Water resource outcomes depend on factors across overlapping watershed, policy, land use, and social contexts (Chang, 2010; Cohen and Davidson, 2011; Griffin, 1999) and the effectiveness of best management practices can be variable. Outcomes from agricultural best management practices can be influenced and limited by biophysical and climate conditions, management and decision-making, as well as the appropriateness of an intervention (Chaubey et al., 2010; Darby et al., 2015; Hamilton et al., 2017). Green stormwater infrastructure and its supporting institutional infrastructure in general needs to “fit” environmental need at site, stream, and catchment scales and be flexible to decision making at the site scale (Ekstrom and Young, 2009; Habron, 2003; Roy et al., 2008). Watershed-level improvement from site and stream segment level implementation of BMPs in agriculture and development depends on comprehensive planning (Roy et al, 2008) and integrated local to watershed scale modeling to target pollution reduction while accounting for opportunities and constraints (Ghebremichael et al., 2013).

1.4.1 Pro-environmental behaviors and motivations are context-dependent

Addressing complex environmental problems requires action across multiple scales. At the individual scale, motivations for pro-environmental behavior are heterogeneous and can vary over time as environmental behaviors become more mainstream (Kollmuss & Agyeman, 2002; Wilson & Dowlatabadi, 2007). External factors that drive environmental behaviors are institutional, economic, social and cultural, while internal factors include motivation, knowledge, awareness, values, attitudes, emotion, locus of control, responsibility, and priority (Kollmuss and Agyeman, 2002). Economic incentives can be important motivators to increase pro-environmental behavior adoption in certain contexts. But predictions of behavior with economic models that ignore social, infrastructure, and psychological factors may fall short (Kollmuss & Agyeman, 2002). In a review of decision making models and residential energy use, Wilson and Dowlatabadi (2008, p192) help capture critical questions for actors promoting adoption of environmental behavior as a challenge of understanding" *where on the individual-to-social, instinctive-to-deliberative, psychological-to-contextual, and short-to-long-term decision continua their interventions are targeted and which of the determinants of decisions they are aiming to influence."*

1.4.2 Complex governance networks

Effective water resource management and adaptation to climate change and shifts within a polycentric governance system (Koliba et al., 2010; Ostrom, 2010; Pahl-Wostl, 2009) require coordination, collaboration, and mobilization of different resources between multiple actors (Biagini et al., 2014; Kiparsky et al., 2012) that cross governance, spatial, and temporal scales. An example of this complexity in terms of water quality can be found in Lubell et al (2014) who point to the need for agriculture extension programs to utilize existing farmer networks and maximize synergy between experiential, technical and social learning that can better address different behavioral motivations and capacities. In Wilson and Dowlatabadi's (2007) study of energy efficiency improvements, they argue that community-level interventions can be most effective when addressing household-level social norms. Valente (2012) describes four social network intervention strategies to accelerate behavior change such as individuals, segmentation, induction and alteration. Interventions could focus on increasing visibility (centrality) of "champions," segmentation approaches that could simultaneously target different groups with appropriate tools, promote diffusion of knowledge through networks, and utilize network dynamics to encourage behavior change (Valente, 2012).

1.5 Multifunctional adaptive solutions across scales

A common language to identify the interdependent and co-occurring actions in management initiatives across different social and physical contexts is important for evaluating strategies, adaptive solutions, and to enable coordination of stakeholders (Biagini et al., 2014). Biagini et al. (2014) present a typology of adaptation actions based on their review of the body of knowledge on climate change adaptation, and a comparison of it to actual funded adaptation projects by the Global Environment Facility. Ten overarching adaptation actions were validated through analysis of existing adaptation projects, including: capacity building, management and planning, practice and behavior, policy, information, physical infrastructure, warning or observing system, green infrastructure, financing, and technology (Biagini, et al., 2014). The typology branches from previous literature and separates “technology” into “information”, “early warning”, and “infrastructure” and “technology” (Biagini et al., 2014). Adaptation actions like vegetated buffers, improved road maintenance practices, and low impact development, provide ancillary benefits in the watershed and can help to increase cost effectiveness regardless of future climate change impacts (UNEP, 2014) and be considered as “no regrets” (Kiparsky et al., 2012) adaptations in terms of climate change uncertainty. The Millar et al. (2007) framework of different types of adaptation strategies categorizes strategies by resistance, resilience, and transformation, leading to successively greater adaptive capacity (Walthall et al., 2013). Adaptation actions can also be reactive, concurrent, and proactive relative to climate change impetus (Smit et al., 2000).

The management and provision of soil health can be an example of meeting multifunctional objectives including agricultural production, water quality and other ecosystem functions (Barrios, 2007; Cassman, 1999; Dominati et al., 2010; Doran, 2002). More recent definitions of soil health encompass broader agricultural and environmental benefits extending beyond biophysical and socioeconomic indicators (Herrick, 2000). A set of desirable physical, chemical, and biological soil properties in agriculture, “soil health,” improves crop productivity and can provide water quality and regulation and nutrient cycling benefits (Amundson et al., 2015; Banwart, 2011; Barrios, 2007; Cassman, 1999; Doran, 2002; Lal et al., 2011). Humans depend on ecosystems directly and indirectly for the provision of goods and services, including food, water supply, nutrient cycling, and climate regulation (Costanza et al., 1997). A recent focus of the soil health literature is the importance of soils in the supplying of supporting, regulating, provisioning, and cultural ecosystem services. These ecosystem services include soil structure, nutrient cycling, water availability and regulation, carbon sequestration, clean water, food production, and biodiversity (Amundson et al., 2015; Banwart, 2011; Barrios, 2007; Dominati et al., 2010; Kibblewhite et al., 2008; Lal, 2004 Cassman, 1999; Doran, 2002). In both industrial and traditional agricultural production systems, soil health has a critical role to play in climate change adaptation through reducing erosion, and increasing carbon sequestration (Lal et al., 2011), and adapting to both drought and intense rainfall events (Altieri, et al. (2015). These soil ecosystem services are critical for continuing to sustain agricultural production, but there is no prescription to achieve these benefits in any given setting (Amundson et al., 2015; Banwart, 2011; Lal, 2015)). Sustainable intensification in agriculture depends on soil fertility and overall quality (Lal, 2015).

Green infrastructure presents multifunctional approaches to stormwater management that can address different needs beyond urban areas (Barbosa et al., 2012; UNEP, 2014), and will be needed to adapt to and manage anticipated climate change impacts including increased precipitation, increased storm intensity, and changes to evapotranspiration, water storage, and drainage capacity (Carpenter et al., 2011; Chang, 2010; Farrelly and Brown, 2011). In developed landscapes, green stormwater infrastructure (GSI) offers on-site solutions that mimic natural ecosystem functions of predevelopment to improve water regulation and water quality by lessening runoff and erosion with pollutants (UNEP, 2014; United States Environmental Protection Agency, 2015). The presence of green space such as GSI can contribute to well-being, health, and social safety, and is a desirable feature in neighborhoods to residents (Bowman and Thompson, 2009; Groenewegen et al., 2006). In these dynamic and complex settings, solutions require engagement, reflection, knowledge and appropriate resources at the local management level in order to be adaptively and effectively implemented over time (Patterson et al., 2013).

Across agricultural and developed landscapes, adaption actions requires social learning and political and social will to change behavior and ruling paradigms and may happen over different time scales (Biagini et al., 2014; Pahl-Wostl, 2009; Van der Brugge and Van Raak, 2007). Adaptationoccurs over a continuum from short-term, tactical to strategic or long-term interventions (Smit et al., 2000) allowing focus and efforts to shift toward finer strategic actions such as changing practice and behavior (Biagini et al., 2014, Kiparsky et al., 2012). For example, accounting for initial establishment barriers, cover cropping in agricultural fields can be designed to fit a farm's management system, and is feasible to implement seasonally or in the short term (Meals et al., 2010; Sarrantonio , and Gallandt2003), while low impact development at a watershed scale encompasses multiple potential practices and stormwater management contexts, which may require social, policy, and biophysical changes to be implemented (Roy et al., 2008; Wright et al., 2016).

1.6 Vermont and phosphorus pollution in Lake Champlain Basin

The research presented in this dissertation consider management of phosphorus pollution in a complex socio-ecological system the Lake Champlain Basin (Chapter 2), use of soil indicators by farmers in two sub-watersheds of the Lake Champlain Basin (Chapter 3), and individual household-scale perceptions of green stormwater infrastructure adoption across the entire state of Vermont (Chapter 4). The state of Vermont is actively engaged in a series of initiatives related to stemming nutrient pollution and harmful algal blooms for its major basins including Lake Champlain, Lake Memphremagog, and the Connecticut River, all of which are transboundary, crossing state and/or national boundaries (VT DEC, 2017). Efforts to clean up Lake Champlain are taken by federal, state, and local governments, the International Joint Commission, non-governmental organizations, concerned citizens, and interest groups (Osherenko, 2013). Through the authority of the United States Clean Water Act, (CWA) the Environmental Protection Agency (EPA) requires the development and implementation of a Total Maximum Daily Load (TMDL) for designated impaired surface water bodies. Vermont has recently resubmitted its phosphorus TMDL for Lake Champlain after its 2002 plan was disapproved in 2010 (Osherenko, 2013; VT DEC, 2016). The Lake Champlain Basin region including Vermont, New York, and Quebec Province of Canada has made efforts to address phosphorus pollution and stem harmful algal blooms since the 1980s (LCBP, 2016; Osherenko, 2013). Studies to develop the TMDL attribute 3.1% of the total estimated phosphorus loading in Vermont to point sources such as wastewater treatment facilities. Non-point sources such as agriculture, developed areas, roads, and forests contribute 39.7%, 13.8% and 5.6% respectively. Forests and stream banks distributed across the landscape also contribute significant amounts of phosphorus, 14.5% and 22.3% respectively (Vermont Department of Environmental Conservation, 2014).

In the United States, the National Pollutant Discharge Elimination System (NPDES) program is one of the major policy tools for point source discharge of runoff from stormwater and agricultural point sources (OW US EPA, n.d.). While there are no designated agricultural point sources from animal feedlot operations designated as confined animal feeding operations (CAFOs) in Vermont, stormwater is regulated through the NPDES program in the state. To address non-point agricultural sources at the state level, Vermont has revised its Required Agricultural Practices rules, and is continuing to invest in technical and financial assistance for farms in order to be positioned to meet the TMDL and the challenge of stemming phosphorus pollution (VTAAFM, 2016a). The phosphorus allocations and reduction targets from agriculture require widespread changes to cropping and management practices, which will create new challenges and opportunities for farms of all sizes in Vermont (State of Vermont, 2015; Wertlieb and Bodette, 2014). For stormwater, the permitting of Municipal Separate Storm Sewer Systems (MS4) addresses "a conveyance or system of conveyances that is: owned by a state, city, town, village, or other public entity that discharges to waters of the U.S.; designed or used to collect or convey stormwater (e.g., storm drains, pipes, ditches), not a combined sewer, and; not part of a sewage treatment plant, or publicly owned treatment works (POTW)" (OW US EPA, n.d., page). Two types of NPDES permits for stormwater and MS4s were established in 1990 and 1999, respectively. In the state of Vermont, all of the issued MS4 permits fall under the Phase II permit (Vermont Department of Environmental Conservation, n.d.) which pertain to small municipal separate storm sewer systems inside and outside of urbanized areas, through a general permit and Notice of Intent (NOI) (US EPA, n.d.-b; US EPA, n.d.-c). The permitting schedule is about every ten years; so the first permits were established in 2004 for nine municipalities and were renewed with three additional muncipalities added in 2012 (Vermont Department of Environmental Conservation, n.d.). All of the MS4 permits issues to muncipalities are in the the Lake Champlain Basin. MS4s are required to meet six minimum control measures including best practices related to construction and post-construction, illicit discharge elimination, and good housekeeping, as well as education outreach, and participation activities (OW US EPA, n.d.).

Given the extent of pollution coming from erosion and runoff in the Basin, the major challenge is to provide reasonable assurances to the public of adequate reductions of phosphorus to the “maximum extent practicable” (State of Vermont, 2015; Stoner, 2011; U.S. Environmental Protection Agency (EPA), 2016) Managing soil, water, and nutrients from these landscapes is further complicated by climate change and increasing temperature, increased greenhouse gases and extreme events that may impact the effectiveness, accessibility, and need for best management practices (Guilbert et al., 2014; Stager and Thill, 2010). Climate change and extreme weather adds even more weather related risk and uncertainty to farming operations and creates a need for strategies to maintain productive and viable farm systems (Schattman et al., 2016, 2017; USDA, 2014). Overlaying these dynamics is also the difficult and uncertain economic reality many farms face (D’Ambrosio, 2016). Agricultural livelihoods and landscapes are bound by environmental, economic, and policy constraints occurring at global, national, state, and local levels, and strategies are needed that can adapt to these dynamics and meet multiple objectives. As stated in the Vermont Phosphorus TMDL for Lake Champlain plan: “The commitments presented in this Phase 1 Plan include new and enhanced regulation, funding and financial incentives, and technical assistance, and build on work already done by the State over the past 10 years to reduce phosphorus contributions to the lake. They will require new and increased efforts from nearly every sector of society, including state government, municipalities, farmers, developers, businesses and homeowners” (State of Vermont, p2, 2015). This dissertation research proposes to understand dimensions of an adaptive and flexible bottom-up approach that can realize multiple solution pathways across agricultural, and developed landscapes amidst climate change, and socio-economic uncertainty.

1.7 Bottom-up adaptive management and stakeholder participation for clean water and healthy soils in a complex social-ecological system

Bottom up adaptive management and stakeholder participation is essential to clean water and healthy soils. Environmental problems exist within a complex social ecological system that needs to be able to manage the challenge of “fit” across scales (Herrfahrdt-Pähle, 2014), as well as varying types of uncertainty (van den Hoek et al., 2014). In addition, a “learning by doing” approach (Walters, 1997) is needed within and across scales in order to facilitate adaptation to change (Patton, 2011). Last, participation is fundamental to allow for cross-scale knowledge exchange (Armitage et al., 2009; Klenk et al., 2015), elicit different ways of knowing (Miller et al., 2008), and to manage tradeoffs between values (Susskind, 2013) (See Figure 1). The research chapters in this dissertation touches on each of these bottom-up adaptive management and stakeholder dimensions that are essential to addressing complex environmental challenges. Chapter 2 evaluates a participatory process to elicit solutions to address pollution in Lake Champlain Basin in the face of climate change. Chapter 3 explores on-farm adaptive management through soil monitoring. Last, Chapter 4 presents a cross-scale analysis of residential green stormwater infrastructure within a complex social-ecological landscape.

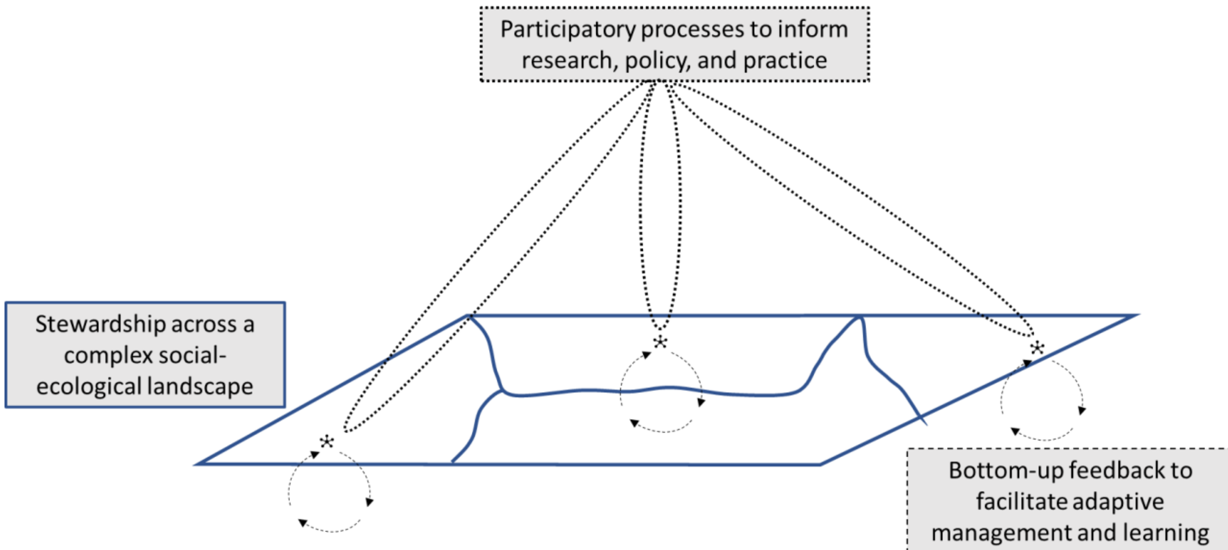

Figure 1-1 Conceptual model of different bottom-up dimensions of addressing complex environmental problems: stewardship across boundaries in a complex social ecological landscape (represented by plane with curved lines) from individual actors (*), feedback to facilitate adaptive management and learning (depicted as arrowed loops), and participatory process to inform research, policy, and practice (ellipses).

1.7.1 Crowdsourced Delphis: Designing solutions to complex environmental problems with broad stakeholder participation

To enable stakeholders to devise solutions that are applicable in research, policy and practice, processes are needed to adaptively define problems from multiple perspectives and to deal with uncertainty (Dietz et al., 2003; Fazey et al., 2014; Patterson et al., 2013; Van der Brugge and Van Raak, 2007). Multiple stakeholder engagement approaches have been discussed in the adaptive management and environmental governance literature, including multi-day focus groups, participatory multi-criteria analysis, participative workshops, and round-tables (Clayton, 1997; Folke et al., 2005; Gregory & Keeney, 1994; Hage, Leroy, & Petersen, 2010; Ker Rault & Jeffrey, 2008; O'Neill et al., 2013; Stirling, 2006). Participatory stakeholder engagement approaches have different benefits and trade-offs related to susceptibility to power dynamics, empowerment, surfacing diverse knowledge types, establishing clear problem bounding and structuring, and usability of outputs (Kalafatis et al., 2015; Mielke et al., 2016; Reed, 2008; Stirling, 2006). With the advancement of information technology and social media tools, new opportunities exist for structuring stakeholder engagement. Stakeholder engagement approaches spanning research, policy, and practice require longer term thinking about sustainable water resource and land management to build adaptive capacity (Fazey et al., 2014; Pahl-Wostl et al., 2007; Peterson et al., 1997). In the first research chapter, I evaluate the ability of a novel crowdsourcing Delphi method to facilitate stakeholder participation and provide emergent, bottom-up feedback about creative solutions and decision alternatives that inform research and policy pathways in the adaptive management of multi-scale environmental problems. An online crowdsourcing Delphi was employed to facilitate generation of solutions from a diverse set of stakeholders, which was used to direct scientific inquiry, develop models, and inform practice, to address the problem of phosphorus pollution coupled with climate change in Lake Champlain Basin (Vermont & New York USA, and Quebec, Canada).

1.7.2 Digging into sustainable soil management: On farm monitoring of soil health

Sustainable soil management strategies are critical to agricultural productivity and avoiding further environmental impacts and degradation of ecosystems (Amundson et al., 2015; Banwart, 2011; Doran, 2002). Soil structure, nutrient cycling, water availability and regulation, carbon sequestration, clean water, food production, and biodiversity are critical soil ecosystem services (Amundson et al., 2015; Banwart, 2011; Barrios, 2007; Dominati et al., 2010; Kibblewhite et al., 2008; Lal, 2004 Cassman, 1999; Doran, 2002). Across all production systems, soils have a critical role to play in climate change mitigation and adaptation through increased carbon sequestration, reduced erosion (Lal et al., 2011), and in the adaption to drought and intense rainfall events (Altieri, et al., 2015). These soil ecosystem services are critical for sustaining agricultural production, but there is no prescription to achieve these benefits in any given setting (Amundson et al., 2015; Banwart, 2011; Lal, 2015). Sustainable management of soil can promote multiple objectives including agricultural production, improved water quality, and other ecosystem functions (Barrios, 2007; Cassman, 1999; Dominati et al., 2010; Doran, 2002; Lal, 2015). Despite the recognition of the importance of soil, a set of soil health practices cannot easily be prescribed (Doran, 2002; Magdoff, 2001) and there are still significant challenges in ensuring sustainable management of this critical resource. Knowledge about complex soil ecosystems and interactions is incomplete (Barrios, 2007; Dance, 2008; Doran, 2002; Herrick, 2000) and farmers need to account for shifting agronomic, environmental, regulatory, and livelihood factors (Schattman et al., 2016; D’Ambrosio, 2016; Wertlieb and Bodette, 2014).

An integrative approach to soil management that can also provide multiple ecosystem services points to a different level of stewardship that promotes flexibility and adaptive management of producers to identify appropriate management solutions, and is not driven solely by top-down selection and promotion of a specific set of technologies or practices (Herrick, 2000). Ingram's (2008) study of producer's tacit and scientific knowledge of soil health found that increased reliance on machinery on some larger farms enabled a loss of a more intimate knowing of soil conditions from when farmers routinely walked their fields and dug in with a shovel. On the other hand, some larger farms were more aware of the agronomic benefits and efficiencies gained through nutrient management and soil health (Ingram, 2008). The provision of soil health benefits to and from agriculture require active engagement and knowledge to promote conditions that can meet multiple management goals (Ingram, 2008; Kelly et al., 2009). Reed et al. (2008) compare indicators derived from scientists and the literature to those that emerged through participatory workshops in Botswana about soil quality and productivity. Reed (2008) point out the scientific and local knowledge can be complementary resulting in a more robust indicator set including early warning signs of degradation. A holistic set of indicators for monitoring soils can comprehensively encompass the complex human-natural system and is preferable to relying on a few indicators that can be potentially misleading (Reed, 2008).

Management practices focused solely on agricultural production can miss opportunities for protecting water quality and providing other ecosystem functions, which depend on managing for soil health (Barrios, 2007; Cassman, 1999; Dominati et al., 2010; Doran, 2002). The engagement of farmers in assessing soil health and quality can be motivated by the desire to validate and examine management practices on the farm, reflecting an adaptive management approach (Romig et al, 1995). De Bruyn & Abbey (2003) point out that farmers are often motivated by the desire to solve problems and implement change, and that soil health knowledge is an asset to understand the impact of land management decision on their soil resources. Producers may rely on processes promoting soil health rather than soil health properties alone (Romig et al., 1995). Agriculture needs to increasingly exchange intensive non-renewable inputs for management approaches that are knowledge-intensive (Pretty, 2008; Starbuck, 1992; Tilman et al., 2002).The second research chapter contributes to understanding farmer monitoring of soil health indicators, their importance for decision making, and implications for broader adaptive management and capacity in agriculture. We use a survey of farmers in Vermont's Lamoille and Missisquoi watersheds that was conducted in 2016 to study monitoring of soil health indicators, relationships to adoption of best management practices, and patterns of adaptive strategies on farms. With soil health objectives at the root of so many agricultural initiatives, this research seeks to understand the importance of soil health information as biophysical feedback, in management decisions, best management practice adoption.

1.7.3 From the Household to Watershed: A cross-scale analysis of residential intention to adopt Green Stormwater Infrastructure (GSI)

The challenge of stormwater management and the need for decentralized approaches like implementing GSI invites engagement from citizens, residents, and property owners (Brown et al., 2016; Green et al., 2012). Governance and management of water resources is occurring at different scales and levels. Boundaries constructed around watersheds, management, and policy arenas can provide technical or governance frameworks to address complex water resource problems, but the challenges are still fundamentally transboundary in nature (Cohen and Davidson, 2011; Susskind and Islam, 2012). The problem of runoff from impervious surfaces can be evaluated across household, neighborhood, infrastructural, watershed, and political boundaries that have different decision-making and management contexts. Realizing downstream benefits of GSI adoption on residential properties requires appropriate siting and selection of practices that can address unique social and physical barriers across different management contexts (Green et al., 2012). Roy et al. (2008) discuss the impediments to watershed scale GSI implementation including 1) uncertainty in the performance and cost effectiveness of GSI, 2) insufficient standards, 3) fragmented responsibilities and components of water being managed separately, 4) multi-jurisdictions, 5) lack of institutional capacity, 6) lack of mandate and 7) lack of funding markets, and 8) resistance to change and risk avoidance. Farrelly and Brown (2011) describe a combined top-down, market-based governance paradigm and call for a system-wide change and avoid piecemeal approaches to regulatory, structural and efficiency mechanisms

Variables influencing individuals' adoption of environmental behavior span multiple dimensions and scales. On the level of individual decisions by property owners, inertia of technocratic institutions, power dynamics, expertise, values, and leadership of stormwater management systems and cause entrenchment of physical and institutional infrastructure create challenges for adoption of GSI (Brown, 2005; Rodriguez et al., 2009; Roy et al., 2008). Keeley et al., (2013) found the lack of a comprehensive stormwater master plan to identify appropriate land to target green stormwater infrastructure to be a major institutional impediment to effectively implementing GSI on the ground in Cincinnati and Milwaukee. Differences in GSI implementation at site level can also be seen across socio-economic demographics where wealthier communities are able to pursue recreational and quality of life enhancements that align with GSI (Barbosa et al., 2012). Also, motivations and barriers can vary across rural and urban settings (Barbosa et al., 2012; Bowman and Thompson, 2009; Groenewegen et al., 2006). Urban motivations for GSI could be related to flooding or high bacteria counts whereas rural motivations for GSI could be related to reducing sediment erosion from unpaved roads, water harvesting for irrigation, preventing habitat loss and controlling invasive species, and receiving payments for ecosystem services from downstream beneficiaries (Barbosa et al., 2012; UNEP, 2014; Wemple et al., 2017). The myriad of social roles that can be motivating for pro-environmental behaviors like energy efficiency, or gardening for wildlife includes display, status, self-expression, conventionality, convenience, security, independence, and flexibility (Goddard et al., 2013; Wilson & Dowlatabadi, 2007). Experience can also be an important motivator to change behavior across individual and institutional scales. Roy et al. (2008) discuss how the recurring drought in Australia led to a shift in paradigms where stormwater was no longer viewed simply as a liability but as a valuable resource.

Multiple studies demonstrate decentralized GSI outcomes depend on hydrological, institutional, and demographic factors (Ahiablame et al., 2013; Barbosa et al., 2012;

Pfeifer and Bennett, 2011; Roy et al., 2008; Wright et al., 2016; Zhang et al., 2015). But research is needed to identify how interactions between spatial, social, and physical factors influence adoption of GSI across a complex social-ecological landscape (Chowdhury et al., 2011). We use a statewide survey of Vermont residents to evaluate how intention to adopt three GSI practices varies with different barriers to adoption, demographics, and multi-scalar stormwater contexts. Specifically, we study intention to adopt GSI within cross-scale stormwater contexts of exposure to site-level runoff, erosion, or flooding, perception of neighborhood-level challenges, town-level stormwater regulation, and watershed impairment in both rural and urban landscapes The final research chapter reveals arrangements of biophysical, social, and institutional factors for GSI adoption that need consideration in promoting sustainable water resource management in a complex social-ecological system (Ostrom and Cox, 2010).

Chapter 2 Crowdsourced Delphis: Designing Solutions to Complex Environmental Problems with Broad Stakeholder Participation

2 Abstract

There is a well-established need for increased stakeholder participation in the generation of adaptive management approaches and specific solutions to complex environmental problems. However, integrating participant feedback into current science, research, and decision-making processes is challenging. This paper presents a novel approach that marries a rigorous Delphi method, borrowed from policy and organizational sciences, with contemporary "crowdsourcing" to address the complex problems of water pollution exacerbated by climate change in the Lake Champlain Basin. In an online Delphi forum that occurred over a six-week period during the Spring of 2014, fifty-three participants proposed and commented on adaptive solutions to address water quality in the context of climate change. In a follow up Multi-Stakeholder workshop, thirty-eight stakeholders participated in refining and synthesizing the results from the forum. To inform modeling and policy dialogue, the resulting list of interventions was analyzed by time horizon, domain, type of adaptation action, and priority level. The interventions suggested by stakeholders within the crowdsourcing forum have contributed to the current policy dialogue in Vermont including legislation to address phosphorus loading to Lake Champlain. This stakeholder approach strengthens traditional modeling scenario development to include solutions and priorities that have been collectively refined and vetted.

2.1 Introduction

The contribution of stakeholder participation to scientific inquiry is an important strategy in promoting an adaptive management approach in policy and practice, and examining alternative stable states and scenarios (Klenk et al., 2015; Peterson et al., 1997). Although the need for increased participation in the generation of solutions is well-established, integrating participant feedback into current science, research, and decision-making processes is challenging (Fazey et al., 2014; Klenk et al., 2015; Reed, 2008). Stakeholder processes are needed to manage uncertainty, adaptively define problems, and expand the set of solutions that can be considered for multiple end-users in research, policy, and practice (Dietz et al., 2003; Fazey et al., 2014; Patterson et al., 2013; Van der Brugge and Van Raak, 2007). High levels of complexity and uncertainty require diverse knowledge and values of multiple stakeholders across scientific and other communities of practice (Folke et al., 2005; Ostrom, 2009; Patterson et al., 2013). Participatory processes that integrate explicit and tacit knowledge can add legitimacy and accountability in instances when science occurs amid ambiguous political, social, environmental, and economic values (Bäckstrand, 2003; Norton and Steinemann, 2001; van den Hoek et al., 2014). The need for stakeholder involvement is demonstrated by the gap between scientific knowledge and the generation of useful adaptation information for decision makers, a gap that persists despite a growing body of literature in climate, hydrological, and engineering sciences (Bradshaw and Borchers, 2000; Fowler et al., 2007; Pahl-Wostl et al., 2007). Without stakeholder engagement, scientific models can present solution sets that mishandle ambiguity and tradeoffs, and oversimplify existing knowledge and experience

(MacMillan and Marshall, 2006; Susskind, 2013; Zia et al., 2011). In the example of water pollution, biophysical models are constrained by imperfect estimates of complex interdependent climate, hydrological, and biogeochemical interactions (Couture et al., 2014; Fowler et al., 2007; Isles et al., 2015). The legitimacy and effectiveness of model outputs for informing decision making are further constrained in that they often do not account for the dynamic, uncertain, and interdependent governance contexts of social-ecological systems (Bäckstrand, 2003; Folke et al., 2005; Pahl-Wostl, 2009; Patterson et al., 2013). When there is no single right or wrong answer in translating science to management, stakeholders can contribute critical input (Bäckstrand, 2003; Clayton, 1997; Moore et al., 2009).

Decision-makers continuously take action to manage land and water resources with present knowledge, priorities, and values (Bradshaw and Borchers, 2000; Kiparsky et al., 2012). Swart et al., (2014) argue climate change adaptation requires a practice-oriented approach that is grounded in scientific inquiry across disciplines. Both biophysical models (Walters, 1997) and a common language (Biagini et al., 2014) are important to understand adaptation and inform management. Biagini et al. (2014) present a typology of adaptation actions based on reviewing climate change adaptation literature, and actual funded Global Environment Facility adaptation projects. Ten overarching actions were identified: capacity building, management and planning, practice and behavior, policy, information, physical infrastructure, warning or observing systems, green infrastructure, financing, and technology (Biagini, et al., 2014). Biagini, et al. (2014) found that implementation depended on the capacities of the communities where projects occurred, underscoring the need to align policy options with community-level capacity.

Multiple stakeholder engagement approaches have been discussed in the adaptive management and environmental governance literature, including multi-day focus groups, participatory multi-criteria analysis, participative workshops, and round-tables (Clayton, 1997; Folke et al., 2005; Gregory & Keeney, 1994; Hage, Leroy, & Petersen, 2010; Ker Rault & Jeffrey, 2008; O'Neill et al., 2013; Stirling, 2006). Participatory stakeholder engagement approaches have different benefits and trade-offs related to susceptibility to power dynamics, empowerment, surfacing diverse knowledge types, establishing clear problem bounding and structuring, and usability of outputs (Kalafatis et al., 2015; Mielke et al., 2016; Reed, 2008; Stirling, 2006). With the advancement of information technology and social media tools, new opportunities exist for structuring stakeholder engagement. Here, we evaluate the ability of a novel crowdsourcing Delphi method to facilitate stakeholder participation and provide emergent, bottom-up feedback about creative solutions and decision alternatives that inform research and policy pathways in the adaptive management of multi-scale environmental problems. An online crowdsourcing Delphi was employed to facilitate generation of solutions from a diverse set of stakeholders, which was used to direct scientific inquiry, develop models, and inform practice, to address the problem of phosphorus pollution coupled with climate change in Lake Champlain Basin (Vermont & New York USA, and Quebec, Canada).

2.1.1 The Delphi method and crowdsourcing

The "Delphi method" is a transparent and robust strategy to interpret factual evidence, and anticipate future solutions and priorities under uncertainty (MacMillan and Marshall, 2006; Powell, 2003; Rikkonen and Tapio, 2009; Webler et al., 1991). In a structured Delphi communication process, a group of participants, typically with expertise in the subject matter, undergo multiple iterations of a questionnaire exercise to discover opinions, determine the most important issues, and identify areas of agreement. Feedback throughout the process is structured via a coordinator to ensure anonymity and to generate the findings and conclusions of the process (Hasson et al., 2000; Linstone et al., 1975; Plummer and Armitage, 2007). In a Delphi group setting, with anonymous participation and repeated phases of refinement, points of consensus and disagreement are validated, and the inhibition of novel ideas (Dalkey and Helmer, 1963), destructive power dynamics, and bandwagon effects creating bias can be avoided (Powell, 2003). The Delphi method can provide a "shortcut" strategy to synthesize and harness complex information promoting an adaptive management approach to decision-making within socio-ecological problems where science is incomplete (Hess and King, 2002).

The Delphi method has been used for a range of applications such as forecasting, decision making, analysis, and scoping, in fields as diverse as technology (Dalkey and Helmer, 1963), commerce (Addison, 2003), nursing (Hasson et al., 2000; Powell, 2003) education (Clayton, 1997), agriculture (Angus et al., 2003; Menard et al., 1999), planning (Hess and King, 2002), public policy (Hilbert et al., 2009), environmental management (Moore et al., 2009; Plummer and Armitage, 2007), ecology (MacMillan and Marshall, 2006), and vulnerability analyses (Brooks et al., 2005; Webler et al., 1991). These different studies address local, regional, national, and global problems and give examples of narrowly and broadly defined "expert" groups of researchers, regulatory authorities, project managers, resource managers, civil society, and contractors (Addison, 2003; Angus et al., 2003; Hess and King, 2002; Hilbert et al., 2009; Plummer and Armitage, 2007; Webler et al., 1991). Traditionally, studies using the Delphi method have used repeated rounds of mail-in questionnaires and semi-structured interviews (Hess and King, 2002; Rikkonen and Tapio, 2009), but examples have also involved group approaches (Webler et al., 1991) and the use of online tools (Hilbert et al., 2009). Mail-in Delphi surveys can be labor and time intensive hampering the study's impact, while a "real-time Delphi" using an online format to gather multiple perspectives reduces processing burden and the study duration (Nowack et al., 2011; Hess and King, 2002).

The interactive, social, World Wide Web and communication technologies have greatly expanded researchers' capabilities of reaching broad audiences, and enabled applications of participatory methods to address scientific, public policy, and societal questions on a massive scale (Crain et al., 2014; Dickinson et al., 2013; Prpić et al., 2015; Wiggins and Crowston, 2011). Examples of applications of crowdsourcing to problem solving, task completion, and idea generation include: Galaxy Zoo, MIT's Climate CoLab, Sustainia and Quirky (Lohr, 2015; MIT Center for Collective Intelligence, n.d.; Prpić et al., 2015; Sustainia, n.d.; Wiggins and Crowston, 2011). Crowdsourcing can take many forms, but refers to the open call for contributions from a large network of people to address a problem (Wiggins and Crowston, 2011). Beyond business, it extends to public policy and planning to surface collective intelligence and creative solutions (Brabham, 2009) through virtual labor markets, tournament crowdsourcing, and open collaboration techniques (Prpić et al., 2015). Prpić et al. (2015) review applications of crowdsourcing to different stages of the policy cycle (Howlett and Ramesh, 1995), with open collaboration being the most common technique.

2.1.2 The case of Lake Champlain Basin and phosphorus pollution

Despite significant efforts over decades to address nutrient pollution (primarily phosphorus), eutrophication and harmful algal blooms persist across portions of Vermont, New York, and Quebec in Lake Champlain (Crawford, 2014; Lake Champlain Basin Program, 2012; Osherenko, 2013) (See Figure 1). The land uses that contribute to phosphorus pollution across the basin include development (stormwater and wastewater), agricultural, forested, floodplain, and riparian land; their settings involve interwoven physical processes, management practices, and governance systems (Patterson et al., 2013; U.S. Environmental Protection Agency (EPA), 2016). The responsibility for cleanup is not under one agency, but is within the purview of federal, state, and local governments, the International Joint Commission, non-governmental organizations, landowners, concerned citizens, the private sector, and interest groups (Koliba et al., 2014; Scheinert et al., 2015). This ambiguity contributes to tension among farmers, city dwellers, and lakefront landowners as well as local governments and national agencies regarding how to effectively mitigate water pollution in the basin (Gaddis et al., 2010). The landscape of phosphorus sources, drivers, and institutions requires adaptive policy and planning solutions that account for climate change impacts and different time lags associated with possible interventions and best management practices (Meals et al., 2010; State of Vermont, 2015). After an earlier plan did not satisfactorily address diverse sources of phosphorus and was revoked, a new Total Maximum Daily Load (TMDL) for the Vermont portion of Lake Champlain Basin, authorized through the United States Clean Water Act (CWA), was required to account for added challenges related to climate change (State of Vermont, 2015; Osherenko, 2013). A draft Vermont TMDL Plan for the LCB was completed in 2015 and accepted by the EPA in 2016. The plan includes new and enhanced regulation, funding and financial incentives, and technical assistance. The plan illustrates the challenge ahead in that these commitments "will require new and increased efforts from nearly every sector of society, including state government, municipalities, farmers, developers, businesses and homeowners" (State of Vermont, 2015, p. 2).

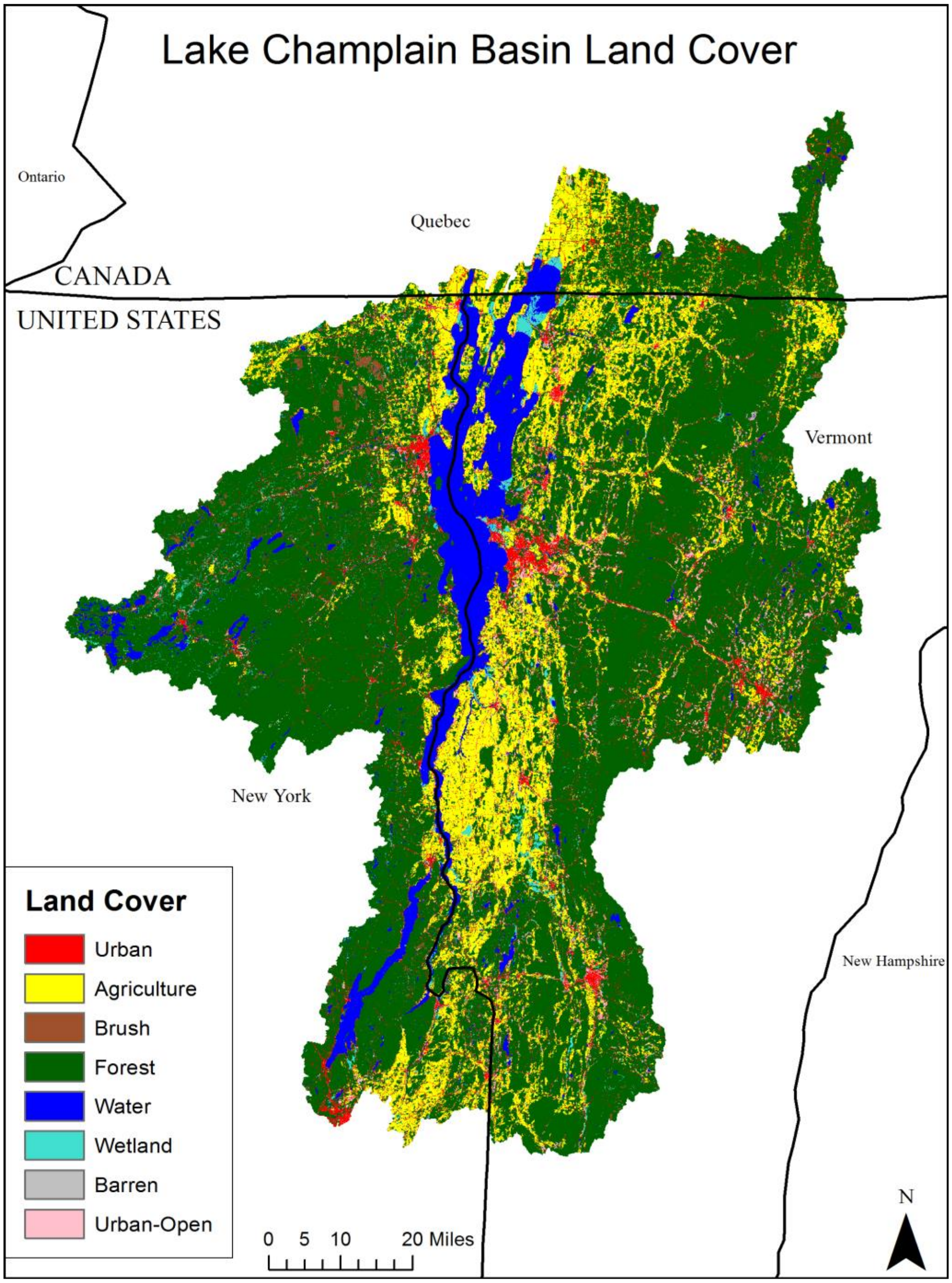

Figure 2-1. Map of Lake Champlain Basin land cover types. Agriculture is estimated to contribute 41% (261MT/yr), forests 16% (101 MT/yr), developed land 18% (114 MT/yr), wastewater treatment facilities 4% (25 MT/yr) and stream banks 21% (130 MT/yr). To meet Vermont's phosphorus TMDL for Lake Champlain a 34% reduction of 213 MT/yr is needed across these sectors. Target allocations for agriculture is 118 MT/yr, forests 82 MT/yr, developed land 93 MT/yr, wastewater treatment facilities 32 MT/yr, and stream banks 71MT/yr, with a margin of safety of 21 MT/yr (U.S. EPA, 2016). Source: Lake Champlain Basin Program, 2007.

2.2 Methods

This research was conducted by a transdisciplinary team, supported by the National Science Foundation-funded Vermont EPSCoR project "Research on Adaptation to Climate Change" (RACC). The RACC team's objectives included research that would help build regional adaptive capacity in the Lake Champlain Basin while studying and integrating governance, land use, hydrological, and biophysical systems (Koliba et al., 2016). RACC brought together major academic, governmental and non-governmental partners in the region. In March 2014, RACC launched Crowdsourcing Solutions to Climate Change in Lake Champlain Basin (CSS2CC.org), an interactive online Delphi forum, to source and identify adaptive interventions from a group of stakeholders over a six-week period. A multi-stakeholder workshop followed the online Delphi forum in May 2014 to refine the interventions. In a structured brainstorming and scoping exercise the online Delphi forum and follow up workshop was established to identify solutions to mitigate water pollution under climate change in Lake Champlain Basin and bring forward collective knowledge and values of stakeholders and experts.

2.2.1 Development of an interactive online forum: crowdsourcing adaptive interventions in an online Delphi forum

The Delphi online crowdsourcing platform used in this research was supported by interdisciplinary expertise in the natural, social, and computer sciences (Crain et al., 2014; Dickinson et al., 2013). As noted by similar initiatives, a web developer was an essential member of the research team, designing a custom site with a simple user interface and capacity for a large audience (Crain et al., 2014; Moore et al., 2009). The online Delphi forum, CSS2CC.org, contained “tabs” for six web pages, organized by: “Introduction and Directions,” “Personal Information,” “My Interventions,” “All Interventions,” “Background Materials,” and “General Discussion.”

The “Background Materials” page provided literature and regional resources on historical climate trends and projections, and current management strategies. Participants were encouraged to review the materials found in the Background Materials page as part of forming their proposed interventions. The collection of materials (Galford et al., 2014; Guilbert et al., 2014; Institute for Sustainable Communities, 2013; Lake Champlain Basin Program, 2012) was not intended to be comprehensive, but to capture some of the salient water pollution and climate change science and highlight examples of key regional efforts in the Lake Champlain Basin. This section also included a network map of climate impacts, which was generated in a stakeholder workshop in the fall of 2012. The “General Discussions” page provided a space for communication with the research team, technical assistance, sharing additional resources, and a general discussion of the online forum itself.

On the “My Interventions” page, participants proposed their ideas for adaptive interventions to promote water quality in the Lake Champlain basin. While it was recognized that many types of interventions and solutions can span multiple “domains,” participants were asked to categorize their interventions within one of the following domains: “Agriculture,” “Stormwater,” “Wastewater,” ‘Forestry,” “Transportation,” “Energy,” “Public Health,” “River Management,” “Development & Land Use,” “Emergency Management,” and “Fish & Wildlife.” For each of their proposed interventions participants provided a title and a rationale comprising a few sentences with details about each intervention (See Figure 2). Participants were also asked to identify the time horizon over which their proposed interventions would likely be able to be implemented, using the definitions here. “Short Term Interventions” were defined as operational interventions that can be implemented, given the existing policy frameworks over a 0 to 12-month time horizon. “Intermediate Term Interventions” are tactical interventions that can be implemented, after some changes are made to the existing policy frameworks, over a 1 to 10-year time horizon. “Long Term Interventions” are strategic interventions that include significant preparation and would be implemented at the 10 to 40-year time horizon.

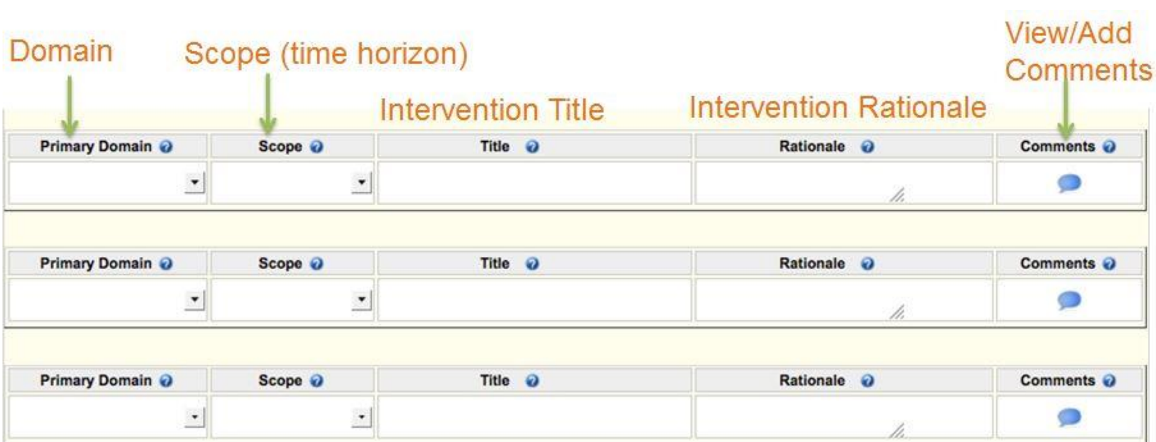

Figure 2-2. Screenshot of “My Interventions” page from the online forum CSS2CC.org. Participants used form to enter interventions with rationale, domain, and time horizon for implementation. Participant comments in an online dialogue about interventions could be viewed and added from this page as well.

From the “My Interventions” page, participants could view other participants’ comments on their interventions and respond by posting new comments. All interventions could be sorted by domain, number of comments, rating, and alphabetically by title, and could be filtered with a keyword search. On the “All Interventions” page, participants could view the entire set of proposed interventions and discussion threads; this encouraged an interactive dialogue through comments and feedback to refine each of the interventions (Figure 3).

Created by member: #69 2014-03-04 08:57:26

Increasing soil health

Primary Domain

Scope: Intermediate+(1-10+yrs.)

Description / Rationale:

Improved soil health can increase infiltration, increase water holding capacity, reduce runoff and reduce needed chemical applications. All of these properties could help alleviate some of the impacts of climate change and improve water quality. Most Champlain farmers are not currently practicing good soil health mangment. More effort, both educational, technical and finacial needs to be made to promote this type of soil managment in the Champlain Basin.

5/5 from 5 votes

Comment

#1 Written by member: #77 2014-03-04 10:17:09 (213)

Enhanced carbon storage and retention of phosphorus should be part of this plan.

#2 Written by member: #47 2014-03-04 10:52:50 (223)

Can you suggest some specific practices that increase soil health?

#3 Written by member: #97 2014-03-05 12:19:50 (231)

Enhanced carbon storage and retention of phosphorus should be part of this plan.
I can imagine the capture of phosphorous by biological systems. Retention of this "captured" phosphorous is not permanent. Is it possible to capture and remove phosphorous from the 'system'? Seems like the best we can hope for is to recycle the phosphorous on land and reduce application of additional phosphorous. Is this possible?

#4 Written by member: #118 2014-03-09 12:17:11 (247)

There are some farmers in the basin incorporating practices to improve the health of their farm's soils thus leading to reduced runoff. These practices include no-till and cover cropping. We need to provide a variety of support for farmers who are employing these practices.

#5 Written by member: #187 2014-03-11 05:22:17 (251)

This is a key strategy in reducing P loads from farm fields.

#6 Written by member: #219 2014-03-21 15:27:45 (300)

Amending turfgrass with organic material and aeration to infiltrate more rainfall and reduce overland transport of sediment and phosphorous is being studied as a stormwater management measure in the upper Great Lakes. There are many possible benefits to soil amendment in many settings.

#7 Written by member: #270 2014-07-17 14:29:01 (387)

Cover Crops!

Figure 2-3. Screenshot of an example of a discussion thread for an intervention proposed on CSS2CC.org and categorized in the Agriculture domain. The screenshot includes the original title and rationale proposed by participant #69 and comments made about the proposed intervention by seven additional participants.

2.2.2 Participant recruitment

To reduce bias in the Delphi forum (Angus et al., 2003), we sought input from a broad pool of stakeholders including experts in the fields of natural and climate sciences, environmental policy and planning, federal agency personnel, state agency personnel, elected officials, town managers, planners, and public work directors, environmental activists, non-profit representatives, technical assistance providers, farmers, developers, leaders from business and tourism, and individual citizens. Close to two hundred organizations and community groups were identified and contacted by email. Prospective participants were contacted through farmer organizations, university list-serves, outreach at the Vermont State House during the 2014 session of legislature, and through individual emails to key stakeholders. The general public was contacted through press releases in the local and campus news, interviews on local television, as well as through classes at local colleges and universities. We estimate that over one thousand individuals heard about the forum, but the precise number of individuals reached cannot be known as a result of using various proprietary list-serves. Gift certificates of twenty dollars to an online website featuring Vermont products were provided as incentives for participation in the forum; participants who contributed interventions and comments to the online forum were entered into a raffle for an Apple iPad.

A new feature was added within a week of launching the website where participants would be notified if their interventions received comments. Updates and reminders were also sent to participants encouraging them to revisit the site each week. In an effort to recruit additional participants, midway through the six-week online forum, the system was modified so that interventions and posted comments could be viewed prior to registering on the website and entering personal/demographic information; this was done to encourage participation by allowing content to draw activity to the site.

The research team initially recruited 204 participants to the online Delphi forum who provided their email addresses to the site and responded to the recruitment appeals. Fifty-three participants went on to complete the personal/demographic information page and suggested interventions and/or commented on other participants' proposed interventions. The majority of the professions were either in non-profit, research, education, or agriculture, but professionals from all levels of government, and from real estate, community development, health, business, and tourism participated. State and federal agency representatives, elected officials, scientists and policy experts, students, and engaged citizens were among participants. 106 interventions were entered during the six-week period.

2.2.3 Generative framing of adaptive solutions from the online Delphi forum

At the end of the six-week online forum, participants' interventions and comments data were analyzed. Repeated interventions were combined, and unclear interventions with no stated mechanism of action were removed, reducing the total number of interventions from 106 to 68. The list of domains was adjusted to fit the set of proposed interventions and feedback in the comments. "Wastewater" was changed to "Wastewater & Waste Management;" "Transportation" and "Development & Land Use" were combined; and "Cross-sector" replaced the "Other" category. "Energy" and "Public Health" were omitted for lack of relevant interventions, and no interventions were proposed in the

“Emergency Management” and “Fish & Wildlife” domains. Original wording by participants was kept as much as possible with the intention of sharing the summary of results at the Multi-Stakeholder Workshop.

2.2.4 Multi-Stakeholder Workshop

Stakeholder workshops can be used as a follow-up to the Delphi method to synthesize and evaluate findings (MacMillan and Marshall, 2006; Moore et al., 2009). In a follow-up to the online Delphi, forum participants, including those who only entered their email addresses in the online forum, were invited to a Multi-Stakeholder Workshop in May 2014. All prior emails, press releases, as well as the regular reminders to contribute ideas to the online forum, included invitations to participate in the Multi-Stakeholder Workshop. Thirty-eight participants met to collectively group and prioritize the solutions that were collected via the online forum. Participants in the workshop were organized into small groups and carried out several activities. First, participants were asked to identify opportunities and challenges for implementation of the 68 interventions that emerged after the online forum, based on various degrees of financial resource availability, distinct policy frameworks, and alternative governance conditions. Next, groups of workshop attendees suggested improvements to interventions, made recommendations for similar and/or complementary interventions to be combined, and proposed additional interventions be added to the list. Last, participants were asked to identify Critical Interventions, defined as being critical to promoting adaptive capacity in the Lake Champlain Basin. Groups were asked to plot implementation projections of these interventions over “short,” “intermediate,” and “long-term” time horizons.

2.2.5 Post-workshop analysis

Comments and additional suggestions from participants in the multi-stakeholder workshop to the list of 68 interventions were analyzed by the research team. Attendees proposed entirely new interventions but most of the input focused on the comments to the interventions that were presented in the workshop. Some comments added improvements, questioned the effectiveness or feasibility of implementing specific interventions, and also suggested some interventions be omitted entirely. In addition, workshop attendees suggested specific interventions to be combined that either would be complimentary together, or to remove redundancy. Synthesis of these comments brought the list to a total of 55 interventions, which reflects the collective input of the participants during the online forum and workshop periods in the spring of 2014.

2.2.6 Framework for analysis of interventions

There are multiple dimensions of the stakeholder-generated interventions that can be analyzed and be beneficial to different questions and problems in research, policy, and decision-making contexts. These interventions were intended to feed in to RACC efforts in two ways. The interventions were intended to inform broader policy and practice dialogue, and they were intended to inform scientific research and integrated assessment models. Using information, tools and laws from multiple disciplines, Integrated Assessment Models "aim to represent complex environmental problems, to identify potential solutions to these problems, and to orient future research" (O'Neill et al., 2013, p. 460). Accordingly, we sought a system for categorizing the interventions for these purposes. The interventions were analyzed by time horizon, domain, type of "adaptation action" as adapted from Biagini et al. (2014), and priority level. The domain and time horizons can be used to model the implementation of different interventions for specific land uses over time. The list of 55 interventions were coded using Biagini et al.'s (2014) adaptation actions as a template for analysis (Crabtree and Miller, 1999) to identify patterns within individual domains and throughout all of the interventions. The projected implementation time horizon ascribed for each intervention was included in the online phase, whereas group deliberation regarding what would be the appropriate implementation periods for the "Critical Interventions" (Section 2.4) took place during the workshop.

2.3. Results

2.3.1 Stakeholder generated solutions: domain, time, adaptation action, and priority

The set of adaptive interventions that emerged through the crowdsourced online Delphi forum and stakeholder workshop spans spatial and temporal scales, and describes a broad set of actors and policy tools (See supplementary materials: Participant Generated Set of 55 Adaptive Interventions). Here, the interventions were classified by domain, time horizon, adaptation action, and priority to initially interpret the rich knowledge embedded in this Delphi forum.

The majority of interventions generated by the online Delphi forum fell in the Agriculture, Development, and Stormwater domains (See Figure 4). Many interventions spanned multiple land uses, despite the assignment of interventions to single domains for the online forum. In the Agriculture domain, examples of short-term interventions included cover cropping and improved manure spreading, increasing soil health (Figure 3) and establishing riparian buffers were characterized as intermediate-term interventions, and restoring a regional nutrient balance, and mining soil phosphorus were identified as long-term interventions. In general, we observed that interventions with significant impacts to livelihoods, revenue streams, infrastructure, management systems, and policy were listed by participants as requiring longer implementation horizons across the domains. By contrast, interventions proposing comparatively simple changes in behavior, or wider adoption of existing practices, were assigned shorter implementation horizons overall.

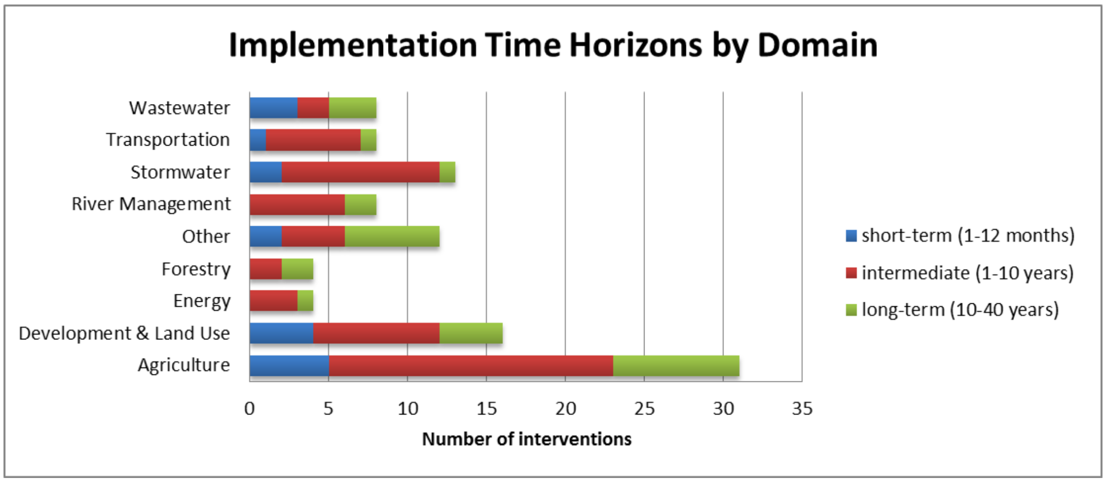

Figure 2-4 Identified implementation time horizons for 106 interventions proposed by CSS2CC.org participants during first phase of the online Delphi forum.

The resulting intervention list after the stakeholder workshop was classified according to the Biagini et al. (2014) typology, which identifies specific actions embedded in adaptation strategies. The majority of the actions proposed within the crowdsourced interventions list can be categorized as "Policy," "Management and Planning," "Practice & Behavior," "Capacity Building," and "Green Infrastructure" (Figure 5). Many of the interventions involve public, private, and non-profit sector actors, and combine more than one adaptation action. For example, one intervention combined four adaptation actions; “Practice & Behavior,” “Policy,” “Green Infrastructure,” and “Management & Planning.” Two interventions combined “Green Infrastructure,” “Management & Planning,” and “Financing.” Five of the interventions combined “Policy” and “Practice & Behavior” actions. Across the domains, the distribution of adaptation actions highlights the several types of financial, political, and social capital required to accomplish many of the proposed interventions.

The most frequent adaptation actions in the Agriculture domain were those related to “Policy,” “Practice & Behavior,” and “Capacity Building.” These agricultural interventions call for changes at the farm level with complementary public support for technical and financial assistance, education, and regulation. Stormwater interventions emphasize technological actions including “Physical Infrastructure” and “Green Infrastructure,” which require capital investments and technical knowledge at the landowner, municipal, and state scales, as well as actions related to “Practice and Behavior,” “Policy,” and “Capacity Building.” The interventions for Development Transportation & Land Use had a greater proportion of adaptation actions in the “Management & Planning” and “Policy” categories, calling for increased environmental regulation, changes to land use policies, and broad shifts in approaches to land use planning.

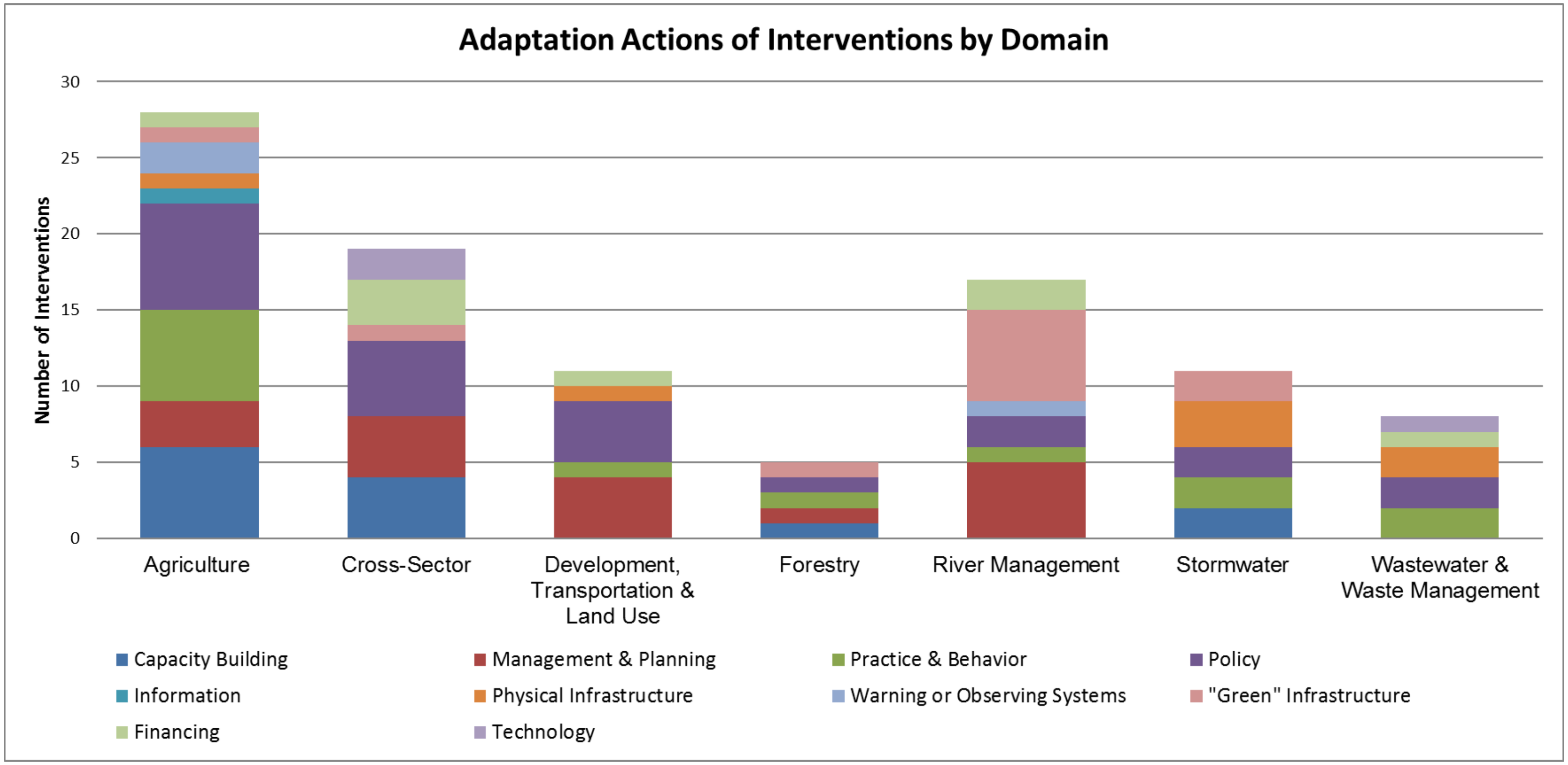

Figure 2-5. Intervention adaptation actions by domain from workshop. (Domain list was adjusted after online forum). Adaptation actions based on Biagini et al. (2014) typology.

Ten “Critical Interventions” were identified in the Multi-Stakeholder Workshop following the online forum, and were thought by the participants to have the most promise to sustain adaptive capacity in the Lake Champlain Basin. Figure 6 shows the list of Critical Interventions and their proposed implementation time horizons, as identified by participant groups in the workshop. The list of Critical Interventions fell within the domains of Stormwater, Development, Transportation, and Agriculture. The Critical Interventions vary in the number and type of actions that are encompassed. Interventions potentially encompassing significant more actions spanned wider implementation time horizons.

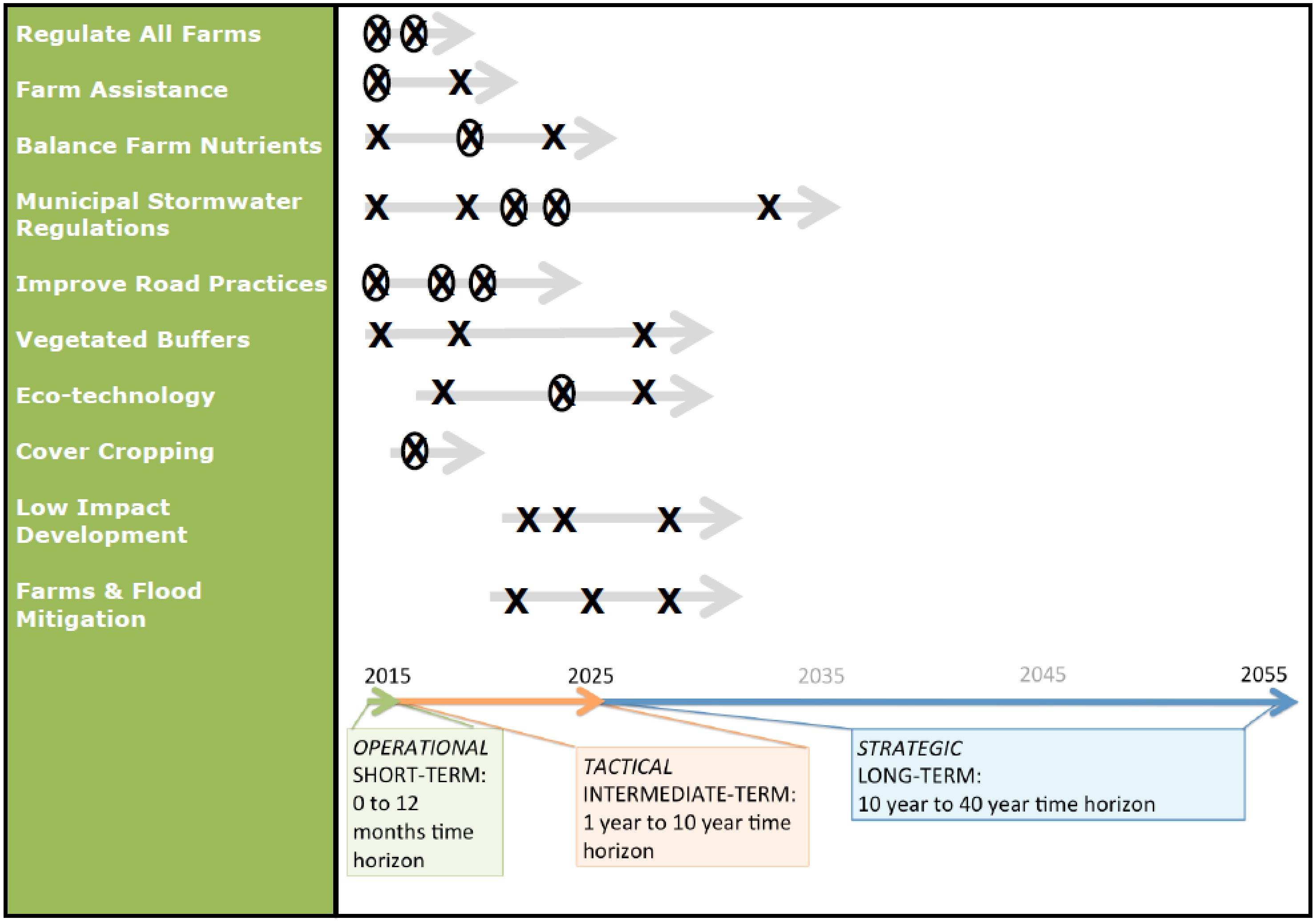

Figure 2-6. Critical Interventions (see Supplementary Materials for full title of each Critical Intervention) and estimated time horizon for implementation identified by participant groups in workshop. Groups' estimate period for implementation is signified by an "X". A circled "X" signifies more than one group identified that time period.

2.3.2 Stakeholder comments and dialogue in the online forum and workshop

The interventions surfaced during the online forum and subsequent workshop generated a dialogue and exchange of ideas between participants about solutions to protect Lake Champlain's water quality. Participants made comments on more than half of the interventions, and a total of one hundred forty-two of their entries added input to original interventions that were proposed. Participant comments sought to clarify and affirm proposals such as, "Give property tax incentives for enhanced stormwater management' and gave ideas for additional dimensions to interventions. Interventions that were perceived to reflect preconceptions or misinformation, often generated clarifications from fellow participants. An intervention proposing to "phase out Dairy" received comments with multiple sentiments including: "Elimination of any group is counter-productive, changing how people behave on the landscape is not;" "Dairy annually accounts for 70-80% of VT's Agricultural Sales...from the perspective of one within the dairy industry, interventions should promote education and financial assistance for dairies to implement and practice ecologically sound practices (i.e. Carbon storing, Habitat restoration, Riparian buffers, permanent vegetation in flood zones, etc.);" "A Vermont without farms will be paved and subdivided, or become a place only for those who can afford to purchase large tracts and keep them idle. People who wish to live in Vermont must have a way to earn their living, and small scale farming offers one way to do so;" and "A great solution to this is the implementation of anaerobic digesters for farms. Not only does this reduce the amount of methane emitted into the atmosphere, it harnesses this GHG into a usable fuel source for farmers. Of course, the up-front costs of this technology are high, multiple farmers can share this cost and technology." Interventions that exaggerated potential effectiveness of solutions, drew input that deepened the dialogue, raising social, economic, political, environmental, and technological considerations.

Participant comments also pointed to existing policy and regulations, and suggested improvements with specific policy tools (incentives, taxes, cost-sharing, etc.), as well as higher-level collaboration, regional watershed management, and opportunities for returns on investment and savings. For example, comments regarding an intervention proposing to develop a water quality mitigation bank included input about existing capacity and limitations in state government, similar existing initiatives, and the need for watershed-level governance as opposed to administration at a municipality level. Comments also highlighted the need for tailoring of interventions with criteria and impact measures, to avoid wasted efforts and unwanted impacts. Some interventions in the Agriculture and Stormwater domains raised comments about cost-benefit ratios and implementation challenges. In addition to the examples in the previous paragraph, an intervention calling for more regulation of small farms included a dialogue about negative economic impacts, and questions about how it could be reasonably enforced. Comments also pointed to a need for more information to be able to guide decisions for infrastructure improvements. For example, a comment that "up to date precipitation data" was needed was added to the intervention calling for "properly sized culverts" to prevent washouts and negative downstream impacts. Participant submission of comments helped create discussion around suggested interventions, added depth to the complexity of the issue, and yielded recommendations for specific contexts.

2.4. Discussion

2.4.1 Analysis of stakeholder generated solutions

The crowdsourcing Delphi yielded ideas for interventions and actions, across domains, revealing specific conditions, capacities, and types of coordination needed between actors providing opportunities to address complex problems (Michelucci and Dickinson, 2016). The greater number of interventions in the Agriculture, Development, and Stormwater domains is likely attributed to these being the major land uses in Vermont that contribute phosphorus to Lake Champlain, and to public perceptions of the water pollution problem (Flagg, 2015; U.S. EPA, 2016; Wertlieb and Bodette, 2014) (See Figure 1). In the case that fewer interventions were suggested for a particular domain, it may be a result of some form of pollution mitigation having already occurred, such as improvements in treatment of Wastewater, or it may be that there is a lesser concern for the domain as it pertains to water quality, such as with the domain of Energy. Evaluation of the projected time horizons for implementation of the interventions from the online portion gives further insight into the incremental and transformative adaptations (Park et al., 2012) that were proposed by participants. In the case of this research, the time horizons were used to cluster interventions so that they could be integrated within broader assessment models that combine social, ecological, and climate dynamics in the Lake Champlain Basin (Zia et al., 2014, 2016). This temporal categorization is recommended for other Delphi processes where changes in inputs over time are a consideration.

The classification of the resulting intervention list according to the Biagini et al. (2014) typology (see Figure 5), identifies common actions throughout the stakeholder solutions. The high incidence of “Policy” and “Management and Planning” as compared to “Physical Infrastructure” or other actions, emphasizes the need for change at the institutional and government levels to promote improved planning, management, and rule making. Where the “Technology”-related actions are generally more financially constrained, the interventions with “Capacity Building,” “Management & Planning,” “Practice & Behavior,” and “Policy” actions reflect the needs for social learning, and political and social will, to change behavior and ruling paradigms (Biagini et al., 2014; Pahl-Wostl, 2009; Van der Brugge and Van Raak, 2007).

The proposed interventions reflect stakeholder preference and perception of what is needed. While more tangible actions such as “Physical Infrastructure” may require more financial capital, they be less difficult to achieve than efforts such as changing “Management and Planning” and “Practice and Behavior,” and may be reflective of differences between achieving incremental and transformative adaptation strategies (Park et al., 2012). The complexity of implementing interventions with multiple adaptation actions (Biagini et al., 2014) that cross governance, spatial, and temporal scales underscores the need for exchange of tools and knowledge within a polycentric governance system (Koliba et al., 2010; Ostrom, 2010; Pahl-Wostl, 2009). The interventions call for action from public, private, and non-profit actors illustrating that effective adaptation and water resource management requires coordination, collaboration, and mobilization of different resources (Biagini et al., 2014; Kiparsky et al., 2012). These different configurations of adaptation actions, across domains and sectors, can be used to model potential future scenarios (Ruiz-Mallén et al., 2015).

Multiple factors likely contribute to the predominance of shorter-term implementation horizons for the Critical Interventions that surfaced in the workshop. This may demonstrate difficulty in adaptation planning when uncertainty increases over longer time horizons (Kiparsky et al., 2012), but also may simply reveal the perception that action is needed immediately to solve water quality problems in the Lake Champlain Basin. For example, accounting for initial establishment barriers, cover cropping in agricultural fields can be designed to fit a farm's management system, and is feasible to implement in the short term (Meals et al., 2010; Sarrantonio and Gallandt, 2003), while low impact development encompasses multiple potential practices and stormwater management contexts, which may require social, policy, and biophysical changes to be implemented (Roy et al., 2008; Wright et al., 2016). Also, many of the interventions can be categorized as "no regrets" (Kiparsky et al., 2012) adaptations in terms of climate change uncertainty. Critical Interventions, including vegetated buffers, improved road maintenance practices, and low impact development, provide ancillary benefits in the watershed and can help to increase cost effectiveness regardless of future climate change impacts (UNEP, 2014). Other interventions are more preventative measures. For example, the magnitude of the benefits from flood mitigation depends on the occurrence of flooding. In addition, uncertainty of future conditions, such as funding, governance systems, policy, and future priorities of society and decision-makers, may have been the cause of disagreement between participant groups about the proposed implementation periods.

2.4.2 Applied crowdsourced solutions for research, policy, and practice

Stakeholder generated interventions from the crowdsourcing Delphi are inputs to scientific inquiry, policy dialogue, and decision-making. A subset of interventions and the analysis described (See Section 3.1) are contributing to the ongoing research on pollution in the Lake Champlain Basin under climate change (Isles et al., 2015; Koliba et al., 2016). Specific stakeholder interventions about land use decisions and best management practices, with varying implementation timelines, were selected from this process and are to be included in forthcoming agent based models of land use (Tsai et al., 2015; Zia et al., 2015). In the effort to evaluate change in a social-ecological system and its governance network (Scheinert et al., 2015), a set of integrated assessment models (Zia et al., 2014, 2016) account for the various actors and adaptation actions embedded in the stakeholder interventions derived from this research, and weighted stakeholder values can be used as additional criteria to prioritize interventions and understand the adaptive management implication of different governance scenarios. Beyond what is demonstrated here, subsequent research and policy agendas could motivate additional analyses of these same interventions to include other key dimensions of inquiry.

The interventions from the crowdsourced Delphi process promote social learning through feedback and exchange of ideas, and new solution spaces to avoid path dependence (Pahl-Wostl et al., 2007). The online Delphi forum already provided a platform for actors predominantly outside of the realm of decision-making to contribute creative solutions to address a complex environmental problem. The stakeholder-generated solutions from the forum described in this research reached the Vermont State Legislature as it was poised to establish capacity and policy to improve Lake Champlain’s water quality (VT-ANR, 2015). The Vermont Clean Water Network (VT Clean Water Network, n.d.) is an example of a current initiative focused on innovation and creating a culture of clean water that is poised to build off of the stakeholder interventions that emerged from the forum and workshop.

Stakeholder engagement approaches spanning research, policy, and practice require longer term thinking about sustainable water resource and land management to build adaptive capacity (Fazey et al., 2014; Pahl-Wostl et al., 2007; Peterson et al., 1997). Including stakeholders in generating solutions can help clarify ambiguity and add legitimacy to the scientific inquiry process that increasingly involves uncertainty, politics, and inherent values (Bäckstrand, 2003; Failing et al., 2004; MacMillan and Marshall, 2006; Reed, 2008). Stakeholder participants in this research represented diverse expertise, types of knowledge, and experience; this broad range of thinking is critical for negotiating goals and achieving innovative solutions (Dietz et al., 2003; Pahl-Wostl, 2009; Susskind, 2013). The integration of stakeholder knowledge in identifying interventions to be tested expands adaptive capacity of the broader system by producing a wider field for creativity and experimentation (Peterson et al., 1997).

2.4.3 The use of a Crowdsourcing Delphi process for stakeholder participation and feedback

The Delphi method and participatory processes in general can face the challenge of maintaining engagement over time (Moore et al., 2009; Reed, 2008). The online forum and workshop involved a month-long campaign and effort to recruit participants from existing formal and informal networks, and many visited the forum but did not contribute their ideas. The legitimacy of the results depends on relative viewpoints being represented that can be challenged if too many participants dropout (Webler et al., 1991). Underrealized quality and diversity of participant engagement likely limited the breadth and depth of proposed solutions and interactive feedback for iterative refinement in the Crowdsourcing Delphi. Hasson et al. (2000) stress the need to clearly communicate to Delphi participants the purpose of the study and required commitment, to maintain involvement over time. Understanding and responding to varying motivations for engagement in these types of forums and making improvements to the online interface could help to improve future participation (Crain et al., 2014; Reed, 2008). Institutional and governance barriers to valuing knowledge co-production with stakeholders also makes an important backdrop to understanding the recruitment and retention challenges associated with this Crowdsourcing Delphi and potential alternative arrangements to facilitate meaningful engagement (Klenk et al., 2015). Commitment over time to participation as a process, and development of empowerment, equity, trust, and learning is more essential than focusing narrowly on participation methodologies and requires institutional support (Reed, 2008). To accomplish this, processes need to be designed to be iterative over time, engaging stakeholders to inform science and decision-making, and adjusting to varying objectives and motivations for participation (Klenk et al., 2015; Ker Rault and Jeffrey, 2008; Reed, 2008; Stirling, 2006; Welp et al., 2006).

The anonymity embedded in the online portion of this process is in stark contrast with participatory workshops and citizen advisory panels approaches previously reviewed

(Ker Rault & Jeffrey, 2008; Gregory & Keeney, 1994; Hage, et al., 2010). Convening participants in person can save time, help maintain participant involvement (Webler et al., 1991), and provide useful exchanges of information and viewpoints (Ker Rault & Jeffrey, 2008), but the lack of anonymity can present destructive power dynamics and limit the development of novel outcomes (Stirling, 2006; Powell, 2003; Clayton, 1997). Clearly identifying the motivations and objectives of participatory engagement (Hage et al., 2010; Renn, 2006; Stirling, 2006; Gregory & Keeney, 1994) can help determine how to balance tradeoffs between anonymous and in-person group dynamics. In this case, the anonymous Delphi online forum enabled individual interventions to be collectively refined and vetted by a broadly defined pool of “expert” stakeholders, resulting in a summative representation of current thinking that reflects diverse perspectives (Dalkey and Helmer, 1963; Fazey et al., 2014; Moore et al., 2009).

The limitations of specific participatory approaches, including the crowdsourcing Delphi discussed here, depend on the objectives and context in which they are implemented (Reed, 2008; Stirling, 2006). Tradeoffs of the Crowdsourcing Delphi are shown when considering this approach as a means to ‘open up’ rather than ‘close down’ discourse using Stirling’s (2006) types of participatory analysis. The creation of an informal network through an online Delphi forum can promote creativity and resilience by identifying opportunities to avoid unfavorable path dependence in predominant management regimes over time (Olsson et al., 2006). A carefully-designed stakeholder forum can foster both “out of the box” thinking and grounded responses, giving vital feedback to address environmental problems. Stakeholder solutions that account for tradeoffs and risk perceptions can help avoid the narrowing of alternatives (Bäckstrand, 2003; Failing et al., 2004). Alternatively, future recruitment of participants could focus on specific types of interventions, or domains, in a focused inquiry set to inform decision-making in research, policy, or practice, serving the function of "closing down" analysis (Klenk et al., 2015; Stirling, 2006). Discourse could focus more narrowly on improving existing policies, practices, or knowledge gaps to address coordination, implementation, or effectiveness challenges. The development of analytical frameworks, encompassing a transdisciplinary research approach (Koliba et al., 2016; Scheinert et al., 2015; Tsai et al., 2015; Zia et al., 2014) can include iterative participatory processes like a Delphi forum to address specific knowledge gaps (Klenk and Hickey, 2011; Stirling, 2006).

The networking, facilitated participation, and resource efficiency benefits of the Delphi method's architecture could be an example of a "distributed moderation system," which has been found to facilitate civil and positive discussions in anonymous online crowdsourcing forums (Lampe et al., 2014) and support transparency and accountability (Hilbert et al., 2009). The iterative phases of feedback to integrate represented viewpoints in a Delphi process can reduce bias, even in the case that results from the online Delphi forum were not exhaustive nor inclusive of all possible ideas (Angus et al., 2003; Clayton, 1997). Through repetition, the Delphi method's suitability, documented process, participant recruitment, and stakeholder-produced list of interventions could be improved over time (Powell, 2003). The set of collectively produced adaptive interventions derived from the online forum and the multi-stakeholder workshop and the process itself will need re-evaluation and continued engagement from stakeholders as new knowledge and capacities are created, and governance and environmental conditions are increasingly understood (Brugnach et al., 2011; Fazey et al., 2014). In particular, interventions from the online forum and workshop that raised concerns about effectiveness and ease of implementation highlight the need of continued development and a participatory process that supports ongoing evaluation (Moore et al., 2009). Equally important, participant evaluation of the ability of the process itself to elicit meaningful outcomes and contributions to research, policy, and practice pathways, and demonstrate the value of stakeholder effort and objectives, is a necessary component of future online and in-person forums that could be easily integrated but requires commitment (Klenk et al., 2015). The online forum's "Discussion" tab provided an opportunity for participants to discuss the forum itself but was underutilized. Eliciting meaningful feedback about participant experiences of stakeholder engagement process requires careful attention. In the future, stakeholder engagement could be iteratively assessed as a stage in the process, including post online forum and workshop surveys to assess participant impressions of the process and its outcomes. Given that the Crowdsourcing Delphi and workshop was designed by the research team, evaluation from multiple perspectives would be a distinct and important feedback mechanism to inform research pathways, promote accountability, and facilitate meaningful knowledge coproduction and adapt over time (Fazey et al., 2014; Klenk et al., 2015; Stirling, 2006).

Crowdsourcing used to harness human problem-solving capabilities in coupled human-natural systems has enormous potential (Crain et al., 2014; Dickinson et al., 2013; Michelucci and Dickinson, 2016; Wiggins and Crowston, 2011). Michelucci and

Dickinson (2016) call attention to the power of crowds in “problem-solving ecosystems,” with iterative ideation, revision, evaluation, and integration rounds. The open collaboration crowdsourcing model (Prpić et al., 2015) could facilitate ongoing dialogues, to test and improve Delphi results, facilitate adaptive management (Hess and King, 2002), and refine the process itself (Rikkonen and Tapio, 2009). In addition to existing research efforts modeling land use decisions and biophysical impacts on the landscape (Tsai et al., 2015; Zia et al., 2015), collective mapping and sharing of geo-coded data could be robust additions to future online forums; geo-location could help to identify and evaluate regional and landscape-wide interventions (Hudson-Smith et al., 2009). The Delphi method can be constructed to elicit processes, designs, or predictions that can be applied to meet multiple objectives, and can evolve to meet new challenges, integrate new information, and respond to change over time. This type of crowdsourcing forum complements other processes that are needed to build trust and expand entry points for stakeholder contribution to bring forward areas of agreement and exchange knowledge around tenable solutions (Clayton, 1997; Olsson et al., 2006; Ostrom, 2010; Susskind, 2013).

2.5. Conclusion

The online Delphi forum and multi-stakeholder workshop combine to form an example of applying a crowdsourcing effort to address real world problems by connecting advances in social web technology with established Delphi research methods. While some research in this area exists, this is largely a new field and there is still a need to establish best practices in crowdsourcing when it is applied to coupled natural-human systems, including developing participant commitment over time, and applying appropriate methods for data analysis. These approaches provide immense opportunities for capacity building and participation that can reveal insights that are not visible through current decision-making and science channels. The interventions that emerged through the online forum and stakeholder workshop described in this research have been used to help validate the current policy dialogue in Vermont and consideration of legislation under review to address phosphorus loading to Lake Champlain Basin. Within a complex adaptive system, the interventions reflect different social, economic, and land use conditions and time horizons for incremental and transformational adaptations (Kates et al., 2012; Koliba et al., 2016; Park et al., 2012). The Crowdsourcing Delphi method presents systematic tools and processes to surface and synthesize expert stakeholder knowledge in a context of uncertainty that can inform parameters for decision-making and priority setting, and support an iterative and

2.6 References

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Chapter 3 Digging into sustainable soil management: On farm monitoring of soil health

3 Abstract

Ongoing attention has been given to soil health as a critical element in the world's ability to sustain agricultural production and avoid continued environmental degradation while adapting to climate change. The fact that soil health encompasses a diverse and complex set of indicators and cannot easily be prescribed to individual farm operations creates a challenge. Healthy soils require knowledge and a long-term commitment to a holistic and adaptive approach, combining practices over time. This research addresses the questions: "to what extent do agricultural producers assess indicators of soil health, and how does feedback inform decisions about farm management?" A survey of farmers in Vermont's (USA) Lamoille and Missisquoi watersheds was conducted in 2016. The importance of soil health information and its use in farm management decision-making was examined in the context of organic and conventional production, land use types, farmer attributes, adoption of best management practices, and broader adaptive capacity. In general, relatively high use of soil indicators and high ratings of their importance were reported for the fourteen soil indicators surveyed. The finding that there were differences in use and perceived importance of soil indicators across management types, demographics, and land use groups has implications beyond the field and farm scale, both for sustainable agriculture, and provision of ecosystem services over time. Three different soil health factors (resilience, transformation, and resistance) influencing management decisions emerged from a factor analysis and varied with adoption of Drainage Ditches, Cover

Crops, and Agroforestry. Soil health feedback and management relates to adaptation strategies including resistance, resilience, and transformation supporting broader adaptive capacity of agroecosystems. With soil health objectives at the root of so many agricultural and environmental initiatives, this research and future inquiries into different contexts and capacity for management of soil health, can provide valuable context to help improve technical assistance and policy approaches to address both agricultural and environmental challenges.

3.1 Introduction

Sustainable soil management strategies are critical to agricultural productivity and avoiding further environmental impacts and degradation of ecosystems (Amundson et al., 2015; Banwart, 2011; Doran, 2002). Soil structure, nutrient cycling, water availability and regulation, carbon sequestration, clean water, food production, and biodiversity are critical soil ecosystem services (Amundson et al., 2015; Banwart, 2011; Barrios, 2007; Dominati et al., 2010; Kibblewhite et al., 2008; Lal, 2004 Cassman, 1999; Doran, 2002). Across all production systems, soils have a critical role to play in climate change mitigation and adaptation through increased carbon sequestration, reduced erosion (Lal et al., 2011), and in the adaption to drought and intense rainfall events (Altieri, et al., 2015). These soil ecosystem services are critical for sustaining agricultural production, but there is no prescription to achieve these benefits in any given setting (Amundson et al., 2015; Banwart, 2011; Lal, 2015). Sustainable management of soil can promote multiple objectives including agricultural production, improved water quality, and other ecosystem functions (Barrios, 2007; Cassman, 1999; Dominati et al., 2010; Doran, 2002; Lal, 2015).

While many of the benefits of healthy soils have been recognized since massive erosion and loss of soil during the United States' Dust Bowl era, recent attention has created a renewed focus on the critical importance of 'soil health'. Some examples include the Food and Agriculture Organization's declaration of 2015 as the "International Year of Soil," national outreach initiatives in the United States like the Department of Agriculture's (USDA) "Unlock the Secrets in the Soil", the establishment of the Soil Health Institute, appearances of soil issues in popular media, and research in leading scientific journals (Gliessman, 2016; FAO, n.d.; USDA-NRCS, n.d.; Barker and Pollan, 2015; Banwart, 2011; Amundson et al., 2015; Kibblewhite et al., 2008; Soil Health Institute, 2016). In response to the Dust Bowl, initiatives in the United States to study and promote cover cropping, crop rotations, contour plowing, manure application methods, strip cropping, erosion control, dry farming, soil drainage, nutrient management, tree cropping, and integrating forests and crop land, were increasingly pursued (Gliessman, 2016). These practices are not new; examples of these systems can be found in traditional farming practices around the world (Altieri et al., 2015). Improving soil quality is a driving motivation for both agricultural and environmental policies that promote best management practices (USDA-NRCS, n.d.). The need to protect soil resources, to meet both farm and public policy goals, is behind the promotion by USDA-NRCS of many agriculture best management practices (USDA-NRCS, 2012).

3.1.1 Digging into Soil health

Over the last half-century, the concept of "soil quality" and "soil health" have taken root within an industrial agricultural paradigm that approaches soil management from a corresponding reductionist approach (Barlett, 1989). There is also some debate about the differences between soil health and quality, with the use of the term "soil health" increasingly replacing the term "soil quality" (Brown and Herrick, 2016). In the past, physical and chemical attributes of soil were the focus of soil assessments, and deficiencies were mainly addressed through soil amendments. Soil-loss tolerance values (T values), millimeters per year of tolerable loss, were established by the USDA in the 1950s to address soil erosion concerns in modern industrial agriculture but it omitted other biological and long-term sustainability dimensions (Montgomery, 2007). Due to economic and political motivations, and a lack of soil production and geological erosion rate data, these values of tolerable erosion were likely set too high to avoid unsustainable soil loss over time (Montgomery, 2007). Some examples of agronomic and policy approaches to improve environmental quality and profitability are still fundamentally reductionist in nature. For example, phosphorus indices, nutrient management planning, and precision agriculture primarily focus on matching inputs and practices with soil and crop requirements (Cornell University College of Agriculture and Life Sciences, 2015; Sharpley et al., 2003; U.S. Environmental Protection Agency (EPA), 2012; VTAAFM, 2016a; Whelan and McBratney, 2000).

By contrast, the literature on soil health describes dynamic and static, abiotic, biotic, physical and social factors (Brown & Herrick, 2016; Herrick, 2000; Ingram, 2008; Romig et al., 1995). Kibblewhite et al., (2008) excellently articulate a need to move beyond a list of independent physical, chemical, and biological properties to an integrated systems approach to soil. Viewing soil as a complex system of multiple biological assemblages, with diverse interdependent functions over different temporal and spatial scales, fundamentally alters soil management paradigms (Kibblewhite et al., 2008). With underlying biological function in mind, different quantities and qualities of organic matter can be an indicator of habitat for biological communities and is a major currency of soil systems (Kibblewhite et al., 2008; Lal, 2015). The vast biodiversity of soils and the importance of soil organisms in regulating nutrients, water, and physical qualities of soils is still not completely understood (Barrios, 2007; Dance, 2008). Increased attention to soil as an integrated living system, and as a medium for the provision of multiple ecosystem services and functions, invites new opportunities and challenges in understanding and managing our approach to agricultural soils.

3.1.2 On farm soil management

To be sustainable, agriculture needs to increasingly exchange intensive non-renewable inputs for management approaches that are ecologically and knowledge-intensive (Pretty, 2008; Starbuck, 1992; Tilman et al., 2002). The dimensions of soil that are emerging point to an increasing level of complexity for management (Lal, 2015). The provision of soil health cannot be prescribed to individual farms and requires active engagement and knowledge (Ingram, 2008; Kelly et al., 2009), and a long-term commitment to a holistic approach to find appropriate solutions (Doran, 2002; Magdoff, 2001). Soil testing is an example of a central best management practice that is widely promoted while its use in informing decisions remains unclear (de Bruyn and Andrews, 2016). Soil properties can be assessed qualitatively or quantitatively, on the farm in real-time, or determined through laboratory testing. Lal (2015) gives a soil quality index that includes physical, chemical and biological indicators with soil organic carbon as a central indicator, but also reminds us that indicators vary by soil type and use. Assessment of soil health properties is difficult and remains imperfect (Doran, 2002). Research efforts have been dedicated to finding valid measures of soil health and identifying accessible and meaningful measures for land managers that are not overly burdensome in terms of time, effort, technical ability, or cost (Cornell University, 2015; Doran, 2002; Herrick, 2000). Farmer participation is essential for appropriate evaluation criteria so that maintaining the multifunctional capacity of soils is oriented to farmer and community level beneficiaries (Reed, 2008) and field contexts.

Management must be relevant to specific agroclimatic and social contexts (Altieri et al., 2015), and the temporal and spatial complexity of soil systems naturally calls for an adaptive management approach that can respond to feedback and changing conditions over time. Our research seeks to contribute to better understanding adaptive strategies through farmer monitoring of soil health indicators and their rankings of importance of these indicators for decision-making. Davidson et al. (2016) describe the multiple definitions of the term resilience across different academic and practice domains and potential confusion that arises in between different approaches to understanding natural and human systems response to disturbance. While these concepts from the resilience literature overlap (Béné et al., 2013; Folke et al., 2010), here we apply Millar et al.,

(2007) and Walthall et al.'s (2013) advocate a mix of short-term and long term adaptive strategies to the study of on-farm soil management. They describe a framework of adaptive strategies to manage disturbances in agricultural and forest ecosystems: creating *resistance* to avoid disruption, promoting *resilience* and capacity to return to desired state, and encouraging *transformation* of a system to new states and conditions (Millar et al., 2007; Walthall et al., 2013). De Bruyn & Abbey (2003) point out that farmers are often motivated by the desire to solve problems, and that soil health knowledge is an asset in understanding the impact of decisions and validating management, reflecting an adaptive approach (Romig et al, 1995). In addition to frequently researched explanatory variables such as farm and individual characteristics (Lockeretz, 1990), this study explores soil health monitoring as a “feedback” variable that may be used in constructing future research of adaptive strategies on farms and adoption of soil conservation practices. The specific research questions we sought to answer were:

1. To what extent do farmers use soil indicators for decision making and does use or ascribed importance of indicators vary with demographic and farm attributes?
2. Are there underlying factors that reflect the variation in the use of the soil indicators for decision-making?
3. Is there a relationship between use of soil indicators and adoption of best management practices on farms?

3.1.3 Study Area: Vermont

Currently a large amount of public attention is focused on the agriculture sector in Vermont and its major role in nutrient pollution and related harmful algae blooms in Lake

Champlain (Banner Baird, 2016; Flagg, 2015). To address this persistent and severe water quality challenge, national and state level policy tools are being strengthened and redesigned. Through the authority of the Clean Water Act, the Environmental Protection Agency recently approved a new Total Maximum Daily Load (TMDL) Implementation Plan for Phosphorus for the basin to reduce loading from the landscape. The revised phosphorus allocations and reduction targets from agriculture require widespread changes to cropping and management practices, which will create new challenges and opportunities for farms of all sizes in Vermont (State of Vermont, 2015; Wertlieb and Bodette, 2014). At the state level, Vermont has revised its Required Agricultural Practices rules, and is continuing to invest in technical and financial assistance for farms to be positioned to meet the TMDL and the challenge of stemming phosphorus pollution (VTAAFM, 2016a). Managing agricultural soil, water, and nutrients from these landscapes is further complicated by climate change and increasing temperatures, annual precipitation, and extreme events that may impact the effectiveness, accessibility, and need for best management practices (Guilbert et al., 2014; Stager and Thill, 2010). Climate change and extreme weather adds even more weather related risk and uncertainty to farming operations and creates a need for strategies to maintain productive and viable farm systems (Schattman et al., 2016, 2017; USDA, 2014). Overlaying these dynamics is also the difficult and uncertain economic reality many farms face (D'Ambrosio, 2016). In addition, Vermont faces an aging farmer population similar to trends in the rest of the country (USDA-ERS, 2017), and while there are fewer farms, new beginning farmers in the state continue to grow (National Sustainable Agriculture Coalition, 2014; USDA

National Agricultural Statistics Survey, 2012). Agricultural livelihoods and landscapes are bound by environmental, economic, and policy constraints occurring at global, national, state, and local levels; and bottom up strategies are needed that can adapt to these dynamics and meet multiple objectives.

3.2 Methods

3.2.1 Survey

Vermont EPSCoR's Research on Adaptation to Climate Change (RACC) project surveyed farmers in Vermont during the summer of 2016 as a continuation of research at the University of Vermont (Schattman et al., 2017). The survey was conducted in the Missisquoi and the Lamoille watersheds, which are representative of the region's mixed forest and agricultural land use (Lovell et al., 2010). The survey was administered by the USDA National Agricultural Statistics Service (NASS) to access a valid representative sample of eligible farmers. The "Farmer Agriculture Resilience Survey" collected data on farm attributes, soil and water resource concerns, participation in conservation programs, adoption of best management practices (BMPs), and nutrient management planning, as well as questions about perceptions of climate change and adaptation behaviors (Schattman et al., 2017). In addition, two questions related to the importance of monitoring individual soil health indicators in decision-making address the research questions of this study (See Supplementary Materials for survey). In total, 112 farmers responded to the survey via personal telephone interviews from the 138 that were contacted (81% response rate) (See Schattman et al., 2017). To be consistent with previous similar studies, survey values were weighted based on farm size (small, medium and large) and management approach (conventional or certified organic) (Schattman et al., 2017).

3.2.2 Soil indicators question, demographics, farm attributes, BMPs and land use

Farmers reported whether they monitored fourteen indicators and how important each soil indicator was for decision-making on their farm on a scale from 0-4. Indicators were monitored or "used" if they marked 1 or higher, and the percentage of farmers who did not use each indicator (and marked "0") is reported. To measure the importance of indicators for decision making, farmers could report "1, monitored; but does not influence decision-making," "2, monitored but infrequently used to inform decision making," "3, monitored and informs decision-making but also depends on other factors," and "4, monitored, and is the main factor for certain farm management decisions." The list of fourteen indicators was developed from a review of the literature, examples of soil health tests, and communication with practitioners and colleagues in UVM Extension and the Plant and Soil Science Department (Cornell University, 2015; Doran, 2002; personal communication, 2015 & 2016). The list of indicators encompasses biological, physical, and chemical properties that are considered key elements to soil health (Cornell University, 2015; Doran, 2002; Herrick, 2000; Lal, 2004; Magdoff, 2001). The indicators are: "Crop yield," "Color and vigor of plants, quality of crop," "Soil organic matter level," "Nutrient content: NPK- nitrogen, Phosphorus, potassium, minor elements," "'Look and feel of soil, soil tilth, aggregate stability," "Infiltration, runoff, ponding, poor drainage" "Topsoil depth," "Signs of erosion (gullies, rills, dust)," "Compaction (surface and/or subsurface hardness)" "Soil moisture and related plant stress, available water capacity," "Soil pH," "Signs of life: earthworms, microbial activity, etc." "Disease pressure and pests in plant and soil," and "Field history (nitrogen credits from previous cropping or cover cropping, residual herbicide carryover, etc.)." The soil indicators are abbreviated below. The proposed list in the survey is not intended to distinguish between methods for soil measurement, or how the information is being obtained, but to present an accessible (Herrick, 2000) list of soil health indicators to assess their use and importance to farmers.

This study used survey data on farmer demographics and farm attributes, as well as adoption of best management practices. For demographic information, age and income data were collected on the ordinal scale, and level of education was on the nominal scale, with median values reported (See Supplementary Materials for survey). Farm acreage and management type, whether farms were certified organic (referring to the USDA (n.d.) designation) were also included. Farmers were also asked about adoption of several BMPs; and a smaller subset for analysis in this study includes Cover Crops, No-till, Drainage Ditches, Agroforestry, and Conservation Buffers. These five practices represent a range of broader management strategies that can be applied in a variety of production settings, including some that have been increasingly promoted through current agri-environmental programs and through technical service provision (Delgado et al., 2011; Janowiak et al., 2016).

To evaluate relationships between use of soil indicators, and land use types, two groups and four sub-groups were identified based on the analysis of the respondents' land use patterns (Figure 1). Respondents reported acreage for different land use and land cover types. Productive land use types included Woodland (pastured and non-pastured), Perennial (including Pasture and Hay), and Annual Crops (Row Crops and Vegetable). About 70% of the respondents (Perennial group) reported no annual crop production. The majority of the Perennial group had pasture and hay land uses together with sub-groups of just Pasture, 14.5%, or Hay, 11.5% which included some fruit production. The majority of farms with annual crop production also had some perennial production as well, but row crop and vegetable production did not overlap in our sample. Of the 21.1% of the sample with Annual Crops, 11.1% were in the Vegetable sub-group and 10% were in the Row Crops sub-group (See Figure 1).

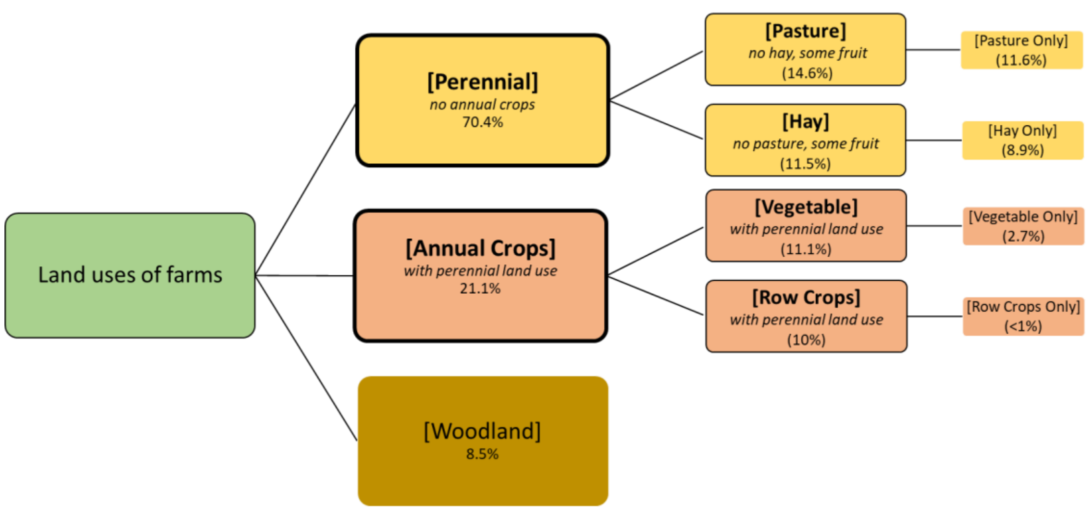

Figure 3-1. Diagram showing 6 land use groups used for analysis of the survey results. Two major land use groups in bold outline: "Perennial land use" and "Annual crops and perennial land use". There are four sub-groups with thin outlines: "Pasture, no hay," "Hay, no pasture," "Vegetable and perennial," and "Row and perennial" from the farmer survey.

3.2.3 Analysis

It is important to understand the environmental, agricultural, and socio-economic contexts in which soil indicators inform management decisions. To initially study the relationship between farm management and production types, Chi-squared tests were used to compare different management and land use groups' use of indicators. Next, the importance of the soil indicators between different groups of land use and management types (Organic or conventional) were compared using ANOVA. Last, to evaluate differences in demographics between groups that used soil indicators to inform decision making, Mann-Whitney U tests were used to compare age, education level, and net income.

A principal component analysis (PCA) was performed, using a varimax orthogonal rotation, on the 14 soil indicators to identify factors with eignenvalues greater than 1 that influence farmers' decision making for those reporting use. The overall Kaiser-Meer Oklin (KMO) measure was 0.745 and Bartlett's sphericity test was statistically significant ($p<0.000$), indicating the data were likely suitable for a factor analysis. ANOVA tests were used again to compare differences in importance of the factors between groups of land use and management types (Organic and conventional). The three soil factors were also used in a oneway analysis of variance (ANOVA) to test for differences in the importance of the three factors between adopters and non-adopters of five practices: Cover Crops, No-till, Drainage Ditches, Agroforestry, and Conservation Buffers.

3.3 Results

Of the farmers that completed the survey, the median age range was 58 to 67 years; completion of an Associates Degree was the median level of education. The median net income range was $0-9,999 indicating that many of the farmers that completed the survey had a net loss of income. The mean total acreage of farms was 200 acres, and the median acreage was 107 acres. Eighteen percent of the farmers who completed the survey were Organic, which reflected a higher representation in the sample than the 7.55% of Vermont farms estimated to be Organic from the 2012 US Agriculture Census (USDA NASS, 2012). Adoption by farms of the five selected BMPs ranged from 46% for Drainage Ditches to 9% for Agroforestry practices (Table 1).

Table 3-1. Descriptive Statistics of demographics, farm attributes, land use, and best management practice adoption for the n=112 respondents from the 2016 Farmer Agriculture Resilience Survey in Vermont.

		Percent (%)	Median	Mean	Std. Error of Mean	Std. Deviation	N
Demographic	Age (years)		58-67				109
	Highest education level		Associate's				107
	Net farm income (2015)		$0-9,999				101
Farm attributes	Certified Organic	18.0					104
	Total acreage		107.3	199.7	25.9	273.9	112
Land use groups and sub-groups	Woodland	8.5					112
	Perennial	70.4					112
	Pasture	*14.6*					112
	Hay	*11.5*					112
	Annual Crops	21.1					112
	Row Crops	*10*					112
	Vegetable	*11.1*					112
Best Management Practices	Cover Crops	21					112
	No-till	14					112
	Drainage Ditches	46					112
	Agroforestry	9					112
	Conservation Buffers	36					112

3.3.1 Soil indicator use and importance

In general, relatively high use and importance were reported across the fourteen soil indicators surveyed. The percent of respondents reporting use of soil indicators ranged from 67.9%, for topsoil depth, to 84.3% for quality of crop. Soil pH had the highest frequency of farms reporting it was a main factor for decision making, while topsoil depth was the least important (Figure 2). Quality of crop, soil pH, disease and pests, crop yield, and signs of life had the most reported use. Quality of crop, crop yield, soil pH, signs of life, and nutrient content were the most important indicators in informing decisions when the two highest ranks were included (3 and 4). While disease and pests was the third most used indicator (80.1%), its importance in influencing decision making ranked relatively lower. For nutrient content, the opposite was true. It had a high overall importance in influencing decision making, but its use as an indicator ranked lower (71.8%).

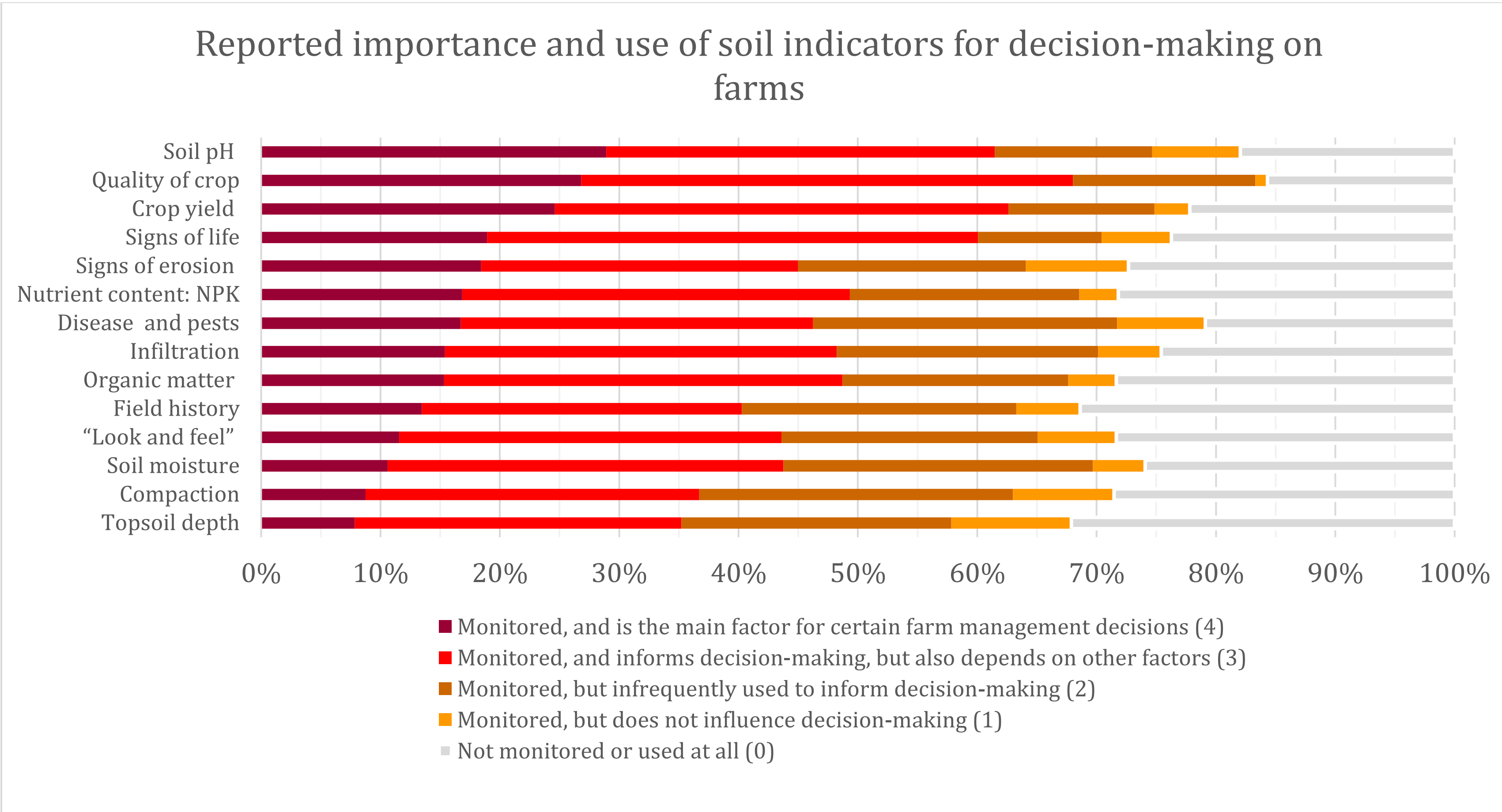

Figure 3-2. Distribution of reported levels of importance of monitored soil indicators for farm management decisions, and overall reported use (cumulative percent excluding farms that reported indicators were not monitored (0) in grey). See Supplementary Materials for survey question (N=112). Indicator list is abbreviated. See Methods or supplementary material for complete phrasing of each soil indicators surveyed.

3.3.2 Difference in use and importance of indicators by group

When the use and importance of soil indicators for decision-making was compared across management types, demographics and land use groups, interesting differences emerged. A significantly greater proportion of Organic farmers reported use of organic matter, nutrient content, compaction, soil moisture, and field history. Howerer, of the 14 soil indicators, only signs of erosion was ranked significantly more important to Organic farmers for decision making. See Tables 2 and 3. For several indicators, average age and income were different between groups that reported use and those that did not. Farmers that used infiltration, topsoil depth, compaction, and field history were generally younger. In addition, farmers that used quality of crop, organic matter, nutrient content, signs of erosion, and disease and pests as indicators had generally higher incomes than farmers who did not use each of these (See Supplementary Materials).

Farmers in the Annual Crop group reported use of the following indicators significantly more than farmers who did not grow any annual crops: look and feel, topsoil depth, signs of erosion, compaction, signs of life, and disease and pests. However, for influencing decision making, organic matter, nutrient content, look and feel, topsoil depth, signs of erosion, compaction, soil moisture, disease and pests and field history was significantly more important for farmers in the Annual Crops group. When analyzing the Row Crops and Vegetable sub-groups, farmers in the Row Crop sub-group reported use of look and feel and signs of erosion significantly more than farmers who did not grow row crops. In terms of influencing decision making, nutrient content was significantly more important for farmers in the Row Crops sub-group There were no differences in use of indicators between the Vegetable sub-group and those who did not grow vegetables. However, some indicators were ranked significantly more important for decision making in the Vegetable sub-group than for farms that did not grow vegetables: quality of crop, organic matter, look and feel, signs of erosion, and disease and pests. (See Table 2 and 3, Figure 1 for group reference)

The differences between soil indicator use and importance for farms in the Perennial group are best described by looking at its sub-groups. The Hay sub-group used look and feel significantly less than farmers whose land use included other types, and farmers in the Pasture sub-group used crop yield, signs of erosion, and compaction significantly less than other farms. The indicator organic matter was significantly less important for the Hay sub-group, and the nutrient content indicator was significantly less important for farms in the Pasture sub-group. See Tables 2 and 3.

Table 3-2. Chi-square comparisons of percent reporting use (respondents reported 1 or greater from Survey question #18, as compared to no monitoring or "0") between Certified Organic (including all land use types) and non-certified production (column 1), and for Perennial and Annual Crops land use groups and their sub-groups: Pasture, Hay, Row Crops, and Vegetable (columns 2-7). Significant differences of ≤0.05 are in bold. Cells in green indicate the group identified at the top of the table used the indicators more; and the opposite is true for cells in red. Indicator list is abbreviated. See Methods or supplementary material for complete phrasing of each soil indicators surveyed.

	"Certified Organic"			"Perennial"			"Pasture"			"Hay"			"Annual Crops"			"Row Crops"			"Vegetable"		
	1	**0**	**Sig**	**1**	**0**	**Sig**	**1**	**0**	**Sig**	**1**	**0**	**Sig**	**1**	**0**	**Sig**	**1**	**0**	**Sig**	**1**	**0**	**Sig**
Crop yield	94	75	0.067*	78	78	0.97	**53.3**	**83**	**.011****	91	76	0.26	91	74	.084*	91	77	0.28	0.92	76	0.21
Quality of crop	94	84	0.251	83	89	0.52	68.8	87	.073*	91	83	0.491	96	81	.091*	100	83	0.13	91.7	84	0.47
Organic matter	**94**	**69**	**0.044****	69	78	0.37	56.3	74	0.142	0	71	0.933	87	68	.070*	91	69	0.14	83.3	71	0.36
Nutrient content: NPK	**94**	**69**	**0.029****	69	78	0.39	62.5	74	0.371	82	70	0.418	83	68	0.147	91	70	0.14	83.3	71	0.37
"Look and feel"	88	72	0.163	**66**	**89**	**0.03****	62.5	74	0.371	**46**	**75**	**0.043****	**96**	**64**	**.003****	**100**	**68**	**.026****	91.7	69	.098*
Infiltration	83	76	0.504	78	70	0.47	75	75	0.98	82	75	0.606	79	73	0.567	82	75	0.61	83.3	74	0.5
Topsoil depth	88	66	0.068*	65	74	0.4	53.8	70	0.25	64	68	0.759	**87**	**62**	**.024****	82	66	0.29	91.7	64	.058*
Signs of erosion	83	71	0.276	70	78	0.47	**46.7**	**77**	**.015****	91	70	0.146	**91**	**67**	**.021****	**100**	**69**	**.030****	83.3	71	0.38
Compaction	**94**	**69**	**0.027****	69	78	0.37	**42.9**	**76**	**0.012****	82	70	0.406	**91**	**66**	**.017****	91	69	0.14	91.7	68	.094*
Soil moisture	**94**	**70**	**0.034****	73	78	0.62	62.5	77	0.241	91	71	0.164	87	70	0.11	91	72	0.18	83.3	73	0.44
Soil pH	94	80	0.14	80	89	0.33	66.7	84	0.104	91	80	0.391	96	78	.054*	100	80	0.1	91.7	81	0.36
Signs of life	94	76	0.092*	72	89	0.088*	62.5	78	177	82	76	0.661	**96**	**71**	**.013****	100	74	.051*	91.7	74	0.19
Disease and pests	94	77	0.095*	76	89	0.17	68.8	81	0.295	82	79	0.832	**96**	**74**	**.027****	100	77	.073*	91.7	78	0.26
Field history	**94**	**65**	**0.019****	68	70	0.79	62.5	70	0.56	82	67	0.309	75	67	0.444	73	69	0.78	83.3	67	0.26

Table 3-3. ANOVA performed on reported value of importance of soil indicators for respondents who reported use of indicators between Certified Organic (including all land use types) and non-certified production (1 and 0, respectively in column 1), and for Perennial and Annual Crops land use groups and their sub-groups: Pasture, Hay, Row Crops, and Vegetable (columns 2-7). Significant differences of ≤0.05 are in bold. Cells in green show significantly greater reported importance of indicators for the group identified at the top of the table; the opposite is true for cells in red. Indicator list is abbreviated. See Methods or supplementary material for complete phrasing of each soil indicators surveyed.

	"Certified Organic"			"Perennial"			"Pasture"			"Hay"			"Annual Crops"			"Row Crops"			"Vegetable"		
	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.
Crop yield	3.3	3.0	0.153	3.0	3.2	0.531	2.9	3.1	0.460	3.1	3.1	0.881	3.2	3	0.531	3.1	3.0	0.577	3.4	3.0	0.181
Quality of crop	3.1	3.1	0.978	3.0	3.3	0.077	3.3	3.1	0.469	3.0	3.1	0.716	3.4	3	0.065*	3.0	3.1	0.67	**3.7**	**3.2**	**0.004*** **
Organic matter	2.9	2.8	0.664	**2.7**	**3.2**	**0.011** **	3.0	2.8	0.546	**2.2**	**2.9**	**0.034** **	**3.2**	**2.7**	**0.036** **	3.0	2.8	0.642	**3.4**	**2.7**	**0.024** **
Nutrient content: NPK	2.9	2.9	0.773	**2.7**	**3.3**	**0.006*** **	**2.1**	**3.0**	**0.002*** **	3.0	2.9	0.625	**3.2**	**2.7**	**0.02** **	**3.4**	**2.8**	**0.05** **	3.1	2.8	0.304
"Look and feel"	2.7	2.8	0.988	**2.5**	**3.0**	**0.027** **	2.6	2.7	0.659	3.1	2.6	0.304	**3**	**2.5**	**0.034** **	2.7	2.7	0.816	**3.3**	**2.6**	**0.013** **
Infiltration	3.0	2.7	0.253	2.7	3.1	0.062*	2.9	2.7	0.458	2.5	2.8	0.341	3.1	2.7	0.062*	3.1	2.7	0.299	3.1	2.7	0.167
Topsoil depth	2.3	2.5	0.49	**2.3**	**2.9**	**0.012** **	2.5	2.5	0.890	2.5	2.5	0.936	**2.9**	**2.3**	**0.012** **	2.9	2.4	0.169	2.9	2.4	0.078*
Signs of erosion	**3.2**	**2.6**	**0.034** **	**2.5**	**3.3**	**0.003*** **	3.0	2.7	0.440	2.5	2.8	0.409	**3.3**	**2.5**	**0.003*** **	3.2	2.7	0.097*	**3.4**	**2.7**	**0.037** **
Compaction	2.4	2.6	0.434	**2.4**	**2.9**	**0.027** **	2.9	2.5	0.230	2.3	2.5	0.453	**2.9**	**2.4**	**0.027** **	2.7	2.5	0.365	3.0	2.4	0.06*
Soil moisture	2.7	2.7	0.83	**2.5**	**3.0**	**0.01** **	2.7	2.7	0.905	2.5	2.7	0.452	**3**	**2.6**	**0.040** **	2.8	2.6	0.458	3.1	2.6	0.055
Soil pH	3.3	3.0	0.231	3.0	3.0	0.883	3.1	3.0	0.635	3.1	3.0	0.740	2.9	3	0.631	2.9	3.0	0.582	3.0	3.0	0.945
Signs of life	2.8	3.1	0.34	2.9	3.1	0.476	3.3	2.9	0.180	2.7	3.0	0.289	3	2.9	0.743	2.9	3.0	0.834	3.1	2.9	0.525
Disease and pests	2.7	2.7	0.911	**2.5**	**3.1**	**0.0048*** **	3.0	2.7	0.230	2.2	2.8	0.067*	**3.1**	**2.5**	**0.015** **	2.9	2.7	0.412	**3.3**	**2.6**	**0.021** **
Field history	2.8	0.9	0.463	**2.5**	**3.1**	**0.012** **	3.1	2.6	0.153	2.6	2.7	0.572	**3.1**	**2.6**	**0.044** **	3.2	2.6	0.099*	3.0	2.7	0.326

3.3.3 Soil factor and differences in importance for management between farms

The Principal Component Analysis (PCA) exposed three factors of soil indicators that influenced farm decision making and combined explained 67.8% of the total variance (Table 4). Indicators on Component 1 with high loadings relate to a factor for decision making that supports resilience of agroecosystems (Resilience_Factor) and explained 26.37% of the total variance. Indicators with high loadings on Component 2 relate to transformation of soil systems and agroecosystems (Transformation_Factor) and explained 22.98% of the total variance. Component 3 explained 18.43% of the total variance and had high loadings for indicators associated with resistance of soil systems to changing underlying agricultural production paradigms (Resistance_Factor) (Millar et al., 2007; Walthall et al., 2013) (Table 4).

Table 3-4. First, three principal components showing the importance of fourteen soil indicators for decision making. Indicator list is abbreviated. See Methods or supplementary material for complete phrasing of each soil indicators surveyed.

	Rotated Component Matrix		
Variables:	**Component 1** (26.37%)	**Component 2** (22.98%)	**Component 3** (18.43%)
Compaction	**0.818**	0.283	0.211
Soil moisture	**0.757**	0.183	0.248
Infiltration	**0.698**	0.224	0.507
Disease and pests	**0.683**	0.491	0.003
Field history	**0.683**	0.112	0.302
"Look and feel"	0.058	**0.846**	0.055
Topsoil depth	0.382	**0.774**	0.064
Signs of life	0.198	**0.711**	0.388
Signs of erosion	0.510	**0.624**	0.187
Organic matter	0.437	**0.583**	0.298
Crop yield	0.189	0.020	**0.850**
Nutrient content: NPK	0.397	0.090	**0.640**
Quality of crop	0.052	0.426	**0.626**
Soil pH	0.439	0.243	**0.567**

Differences in the importance of the Resilience, Transformation, and Resistance, factors were tested among the management and land use groups using ANOVA tests. Since the soil indicators for the factor components were measured on a scale from 1 to 4, where 1 had no influence on decision making, and 4 was the main factor for certain farm management decisions, a higher factor score meant the factor was more influential for decision making. The Resilience and Transformation soil factors were significantly more important for decision making among Annual Crops farms, compared to producers managing Pasture and Hay. For the Vegetable sub-group, the Transformation_Factor was significantly more important for decision-making (See Supplementary Materials).

The three soil factors were also used in a oneway analysis of variance (ANOVA) to test for differences in the importance of the three factors between adopters and non-adopters of five practices: Cover Crops, No-till, Drainage Ditches, Agroforestry, and Conservation Buffers. We see that the importance of the soil factors differs. Cover Crop adopters had significantly higher factor scores for the Resilience_Factor, but there was no difference in the importance of the other two factors between Cover Crop adopters and non-adopters. For adoption of Agroforestry, the Transformation_Factor was significantly more important for adopters. Drainage Ditches adopters had significantly higher factor scores for the Resistance_Factor but there was no difference between the other factors. See Table 5. The ANOVA models for No-till and Conservation Buffers did not have significant differences between the soil factor values. (See Supplementary Materials).

Table 3-5. ANOVA table showing differences in values of Resilience, Transformation, and Resistance factor between adopters and non-adopters of 3 practices: Cover Crops, Agroforestry, and Drainage Ditches. Significant differences between adopters and non-adopters are in BOLD.

		Cover Crops					Agroforestry					Drainage Ditches				
		Sum of Squares	df	Mean Square	F	Sig.	Sum of Squares	df	Mean Square	F	Sig.	Sum of Squares	df	Mean Square	F	Sig.
Resilience	Between Groups	**4.486**	**1**	**4.486**	**4.770**	**0.034**	0.263	1	0.263	0.253	0.617	2.462	1	2.462	2.494	0.122
	Within Groups	**40.438**	**43**	**0.940**			44.661	43	1.039			42.462	43	0.987		
	Total	**44.924**	**44**				44.924	44				44.924	44			
Transformation	Between Groups	2.483	1	2.483	2.516	0.120	**7.180**	**1**	**7.180**	**8.180**	**0.007**	2.363	1	2.363	2.387	0.130
	Within Groups	42.441	43	0.987			**37.744**	**43**	**0.878**			42.561	43	0.990		
	Total	44.924	44				**44.924**	**44**				44.924	44			
Resistance	Between Groups	0.621	1	0.621	0.603	0.442	0.069	1	0.069	0.066	0.798	**3.870**	**1**	**3.870**	**4.053**	**0.050**
	Within Groups	44.303	43	1.030			44.855	43	1.043			**41.054**	**43**	**0.955**		
	Total	44.924	44				44.924	44				**44.924**	**44**			

3.4 Discussion

3.4.1 On farm soil management

Although it is not possible to know exactly whether the use and importance of soil indicators from this study would have been different twenty or thirty years ago, these findings may be part of a larger trend of increasing awareness of the importance of soil health (Barker and Pollan, 2015; FAO, n.d.; Gliessman, 2016). More than two-thirds of respondents used indicators, with each indicator having some level of ascribed importance in decision making. Many studies examine farmer soil health knowledge and assessment in general (de Bruyn and Abbey, 2003; Ingram, 2008; Kelly et al., 2009). These interdependent soil indicators imply simple to complex soil ecosystem attributes *and* management responses (Doran, 2002; Herrick, 2000). In a study of soil-water infiltration under different land uses, Bharati et al. (2002) illustrate relationships between overgrazing in pastures, compaction, and poor infiltration. Soil attributes that are more stable and minimally affected by management (Herrick, 2000), like topsoil depth, may not be a recurring factor for decision-making. Some soil indicators precede others in initial priority and may also be accompanied by relatively less complicated management responses; e.g. inputs may help to temporarily achieve appropriate soil pH or nutrient content NPK levels, but are still interdependent with soil organic matter and other soil health attributes (Kibblewhite et al., 2008).

The differences identified in use and importance of soil indicators across management types, demographics, and land use groups can have important implications for sustainable agriculture and provision of ecosystem services over time beyond the field and farm scale (Dominati et al., 2010; Doran, 2002; Lal et al., 2011; Montgomery, 2007). The finding that the farmers using soil indicators were on average younger than their counterparts is similar to findings from Prokopy et al.'s (2008) review of best management practice adoption, but may still not be surprising (Lockeretz, 1990). Difference in income between farmers that monitored soil organic matter and soil erosion and those that did not is in line with literature discussing linkages between soil organic matter and the importance of reducing erosion for agricultural production and profitability (Doran and Zeiss, 2000; Lal, 2006; Maeder et al., 2002). Organic matter, nutrient content, compaction, soil moisture, and field history are equally important attributes for both Organic and conventional production, but this study found differences in use of soil indicators between Organic and conventional farming. Increased dependence on *external* inputs in conventional farming could help explain these soil management differences (Maeder et al., 2002), as well as differences in social networks, attitudes, and access to information, all of which are associated with adoption of best management practices (Prokopy et al., 2008).

The land use groups in this study are each influenced by sets of management practices and constraints, and pathways for risk of degradation of resources. Given that annual crop production presents more challenges related to soil erosion and loss of organic matter due to soil disturbance, along with different nutrient requirements, it is reasonable that there was increased use and ranking of importance of indicators for the Annual Crop group. However, perennial production can encounter challenges for protection of soil and water resources without appropriate management (Bharati et al., 2002; Chaubey et al., 2010; Tilman et al., 2002). While management options may be more limited, or more subtle, in perennial systems, the differences noted here in use of soil indicators (i.e. signs of erosion, compaction, and look and feel) may present risk if a broader strategy is to convert marginal agricultural land to perennial production (Glover et al., 2010; VTAAFM, 2016). Ingram's (2008) case study of farmers and advisors in England points to examples of soil knowledge informing agricultural management decisions, and cases where there is a disconnect between knowledge and management, despite some having first-hand challenges with erosion, compaction, and drainage problems.

The range of capacities to assess and manage soil resources may also relate to broader conditions on farms. Although analysis of resilience is beyond the scope of this research, it is important to recognize the complexity involved in the ability of agroecosystems to persist and recover from disturbances (Cabell and Oelofse, 2012; Folke et al., 2010; Gunderson, 2000; Holling, 1973; Seybold et al., 1999; Walker et al., 2006). For example, human capitals such as income, age, education, and experience, support capacity to maintain systems through disturbance (Prokopy et al., 2008) and may influence incremental and transformative adaptations pursued over time (Park et al., 2012). In this research, the differences in income and age with use of soil organic matter and signs of erosion may also relate to underlying social conditions that can impact a systems' resilience and capacity to pursue different adaptive strategies. While there are limitations to the applications of the concept of resilience to address sustainable development goals (Béné et al., 2012, 2013, 2016) and ambiguity across domains (Davidson et al., 2016), Cabell and Oelofse (2012) suggest instead to focus on behavior-based indicators of resilience promoting adaptation and transformation.

3.4.2 Resistance, resilience and transformation: strategies for soil management

Given the challenge of climate change and degradation of ecosystems the need for adaptive strategies in soil management is an inherent component of a broader paradigm shift in agriculture. The Millar et al. (2007) framework of different types of adaptive strategies, discussed in a recent USDA report (Walthall et al., 2013) on climate change and agriculture, reflects successively greater adaptive capacity and gives a valuable explanation for the soil health factors that emerged. The Resistance_Factor presented here reflects many traditional "agronomic" indicators for management approaches to industrial agriculture. While soil pH, nutrient content, crop yield, and quality of crop can respond considerably to management practices, these soil indicators reflect key components of the predominant reductionist agricultural system and prioritize immediate returns (Millar et al., 2007). The Resilience_Factor includes indicators that can promote a return to agroecosystem function and productive capacity after a disturbance. While indicators that loaded highest on the resilience factor may be slow to recover if degraded (USDA-NRCS, n.d.), and may be more costly and difficult to manage, positive condition is critical to increasing resilience of ecosystems after disturbance (Janowiak et al., 2016). Last, management of soil indicators that loaded high on the Transformation_Factor (soil erosion, soil organic matter, signs of life, etc.) reflect shifts in the structure and function of the agroecosystem that may be more adaptive to disturbance over the long term (Janowiak et al., 2016; Lal et al., 2011). In addition to the Millar et al. (2007) framework there are other dimensions of these soil factors worth exploring. These factors span short, medium, and long term horizons for management, and parallel the broader soil quality and soil health paradigms that have evolved from simple and reductionist to increasingly complex models integrating physical, chemical, and biological properties (Dance, 2008; Herrick, 2000; Kibblewhite et al., 2008; Young, 2014).

The resistant, resilient, and transformative factors relate to adaptive strategies for management from Millar et al. (2007) and Walthall et al. (2013) and differ from the resistance and resilience properties of soil described in soil science literature with regard to response to disturbances (Herrick, 2000; Seybold et al., 1999). For example, while the indicator of nutrient content (loaded highest on the Resistance_Factor) could be responsive to temporary applications of inputs, it may not be indicative of a soil's resistance to disturbance. Indicators like soil organic matter (that loaded highest on the Transformation_Factor) may present more soil-science-based 'resistance' or 'resilience' (Herrick, 2000; Seybold et al., 1999) as a function of underlying biological processes (Barrios, 2007; Kibblewhite et al., 2008; Lal, 2015). Change towards a holistic soil and agroecosystems approach evokes Gliessman's (2004) outline of three levels of conversion to sustainable agriculture, where the first simply focuses on increased efficiency of inputs, the second on increased substitution to improve environmental outcomes, and the third focuses on a fundamental shift of underlying ecological processes. A soil health paradigm that moves beyond an input-based approach to managing soils to using the emergent properties of a functioning soil ecosystem can help reduce the need for inputs to the agricultural production system, or avoid inputs altogether (Gliessman, 2004; Kibblewhite et al., 2008).

Farmer attributes, management systems, policy, and environmental conditions create a complex array of opportunities and constraints to implementing adaptive strategies and adoption of best management practices to support soil health (Carlisle, 2016; Ingram, 2008; Miller, 2014; Prokopy et al., 2008). The links between the land use groups and the ranked importance of soil factors may have implications for differences in adaptive capacity across production systems but more research investigating these linkages is needed. The assumption that perennial systems are more adaptive, resilient to climate impacts, and protective of natural resources depends on the provision of some critical soil ecosystem services and requires active management to ensure desirable functions (Tilman et al., 2002). For example, Chaubey et al.'s (2010) study of BMP effectiveness in pasture-dominated watersheds found that overgrazing increased nutrient loss preventing downstream water quality improvement. The negative impact of overgrazing was simulated even though the SWAT model they utilized did not include compaction or infiltration parameters related to overgrazing which also have hydrological impacts (Chaubey et al., 2010).

The differences in the values of the soil factors between adopters and non-adopters of Cover Crops, Agroforestry, and Drainage Ditches, adds support to the use of the Millar et al. (2007) framework for understanding how different adaptive strategies for soil influences management decisions, and potential feedback between BMPs. Many practices can enhance resilience of agricultural systems including cover crops and agroforestry reviewed here (Janowiak et al., 2016; Noordwijk, n.d.; Sarrantonio and Gallandt, 2003; Walthall et al., 2013). For example, cover crops can help to slow soil erosion rates in extreme rain events helping to enhance agricultural systems (UDSA). Given the predominant agricultural models of today, agroforestry practices represent not just resilience, but a fundamental transformation in management. While Agroforestry practices were reported by about one-tenth of the respondents, the integration of trees into agricultural landscapes is a long-term strategy, requiring commitment to increase adaptive capacity through structural changes to soil and agroecosystems over time (Noordwijk, n.d.). Drainage ditches as a water management strategy in agricultural landscapes may defend against increases in annual precipitation helping to maintain current agricultural production systems (Janowiak et al., 2016; Walthall et al., 2013) but can also act as conduits of nutrients and sediments to receiving waters (Sharpley et al., 2007).

3.4.3 Research, extension, and policy for sustainable soil management on farms

Sustainable management of land resources fundamentally depends on landowners' decisions and their ability to effectively select and implement conservation practices (Tilman et al., 2002).

On the farm, Romig et al. (1995) found that producers often relied on the presence of *processes* that promote soil health rather than *properties* of soil health alone. Laws (2017) offers examples of farmers' implementation of practices to prevent winter erosion and increase water holding capacity to build soil health. Increased awareness of soil health can also stem from implementation and experiences with best management practices, which can function to further stewardship and knowledge of soil resources (Ingram, 2008), implying feedback between BMPs and soil health knowledge. The challenge of shifting to knowledge-intensive behaviors and new management practices cannot fall to farmers alone (Tilman et al., 2002). Effective technical assistance and supporting policy is needed to support sustainable soil management practices on farms.

A major opportunity for technical assistance networks is to leverage horizontal farmer-to-farmer networks in order to optimize social learning and magnify innovators and "positive deviants" (Biggs, 2008; Pant and Hambly Odame, 2009; Prokopy et al., 2008; Valente, 2012) in pursuing a mix of appropriate adaptive strategies. Technical assistance is primarily a top-down model for dissemination of information from experts (agronomists, researchers, scientists) to farmers (Lubell et al., 2014). But technical assistance networks need to be flexible in order to be adaptive to changing needs over time and allow for innovation around soil health and best management practices (Klerkx et al., 2010). Continued research is needed to capitalize on existing farmer knowledge, capacity, and innovation and to target outreach efforts more effectively. For example, the Vegetable and Row Crop sub-groups report greater importance of resilience and transformation factors, but may need technical assistance to identify appropriate management practices. The difference in use of signs of erosion between conventional and Organic farmers reveals an opportunity gap for improved soil management that could be addressed with targeted outreach and education campaigns to farmers with specific conventional production systems. Conventional farmers who monitor soils to inform decision-making could be identified as “positive deviants” to leverage the power of social norms and farmer networks in promoting resilient soils (Biggs, 2008; Lubell et al., 2014).

Sustainable soil management on farms requires policies and investment in a mix of adaptive strategies and practices across scales to promote sustainable agroecosystems. Effective transitions of adaptive strategies along the resistant, resilient, transformation spectrum (Millar et al., 2007; Walthall et al., 2013) requires research, education, extension, and appropriate policies to support sustainable management of soil resources and the wider food system (DeLonge et al., 2016; Miles et al., 2017). DeLonge et al., (2016) and Miles et al., (2017) describe significant challenges for transitioning to sustainable agriculture in the United States. Most of the dollars spent in public investment in research and extension have to do with enhancing yields (DeLonge et al., 2016; Miles et al., 2017) which may not be an effective strategy for providing adequate food security and environmental protection (Ponisio and Ehrlich, 2016). Miles et al. (2017) argue for prioritizing whole systems research to comprehensively tackle problems, as well as a suite of policies to "push away" from unsustainable practices and "pull" towards sustainable alternatives. Policies that promote protection of soil resources, that utilize a mix of adaptive strategies over the short and long term (Millar et al., 2007; Walthall et al., 2013), are central to the food production and supporting resilience to changing conditions (Morris and Bucini, 2016).

3.4.4 Limitations and future research

The survey employed in this study provided a valuable description of basic soil health monitoring and relationships between populations and BMP adoption, but we also recognize that meanings of "use" and 'importance" can vary among respondents. Future research would benefit from understanding how these indicators inform decision making within temporal, demographic, and production contexts and how it can inform technical and financial assistance provision. To be able to understand how these soil indicators can adaptively influence decision-making, future studies could benefit from investigating the different land-use and management contexts for assessment, and how use and importance might vary over time and during the succession of agricultural production in a field (Brown and Herrick, 2016; Herrick, 2000). Addressing these questions in the future would likely benefit from qualitative research methods including focus groups and interviews (Prokopy, 2011), although requesting that farmers make a lengthy time and possible travel commitment is an important consideration and possible limitation for research.

We also recognize that soil health knowledge, particularly the role of biological communicates in complex interactions is incomplete (Barrios, 2007; Dance, 2008; Kibblewhite et al., 2008; Lal, 2015). Our understanding of indicators of soil health and implications for management will continue to evolve. Despite uncertainty, this research examining soil monitoring based on current knowledge and relationships to management strategies is important for understanding broader adaptive strategies on farms. Similarly, while this study inherently seeks to examine farmers' adaptive management using feedback from soil monitoring, we recognize that the list of indicators was developed without direct farmer participation. Future studies would benefit from building off of studies assessing farmer knowledge and engagement with soil health. As Reed et al. (2008) point out, "despite the recognition that sustainability and conservation goals can only be met with active participation from local communities, the majority of indicators are still developed by academic researchers and/or policy-makers" (p1253). Multiple ways of knowing soil can be valuable to managing agricultural resources sustainably (Hendrickson et al., 2008; Liebig and Doran, 1999; Reed et al., 2008) given the importance of provision of soil ecosystem services at the farm scale and beyond.

Sustainable stewardship of soil resources is one example of using knowledge-intensive processes to inform decision-making that are needed for a broader sustainable agriculture approach (Pretty, 2008). There would be enormous value in future research examining how different soil management approaches and the adaptive strategies discussed here fit within a larger sustainable agriculture context. This research was motivated by a larger question about bottom-up monitoring and its potential to inform site-specific stewardship and adaptive management given there is no one-size-fits-all solution. This study presents soil assessment as a "feedback" variable that may be used in constructing future research of farm adaptive capacity and adoption of soil conservation practices.

3.5 Conclusion

Achievement of soil health in agricultural landscapes without the engagement of land managers is impossible. While immediate and short-term action is needed to protect agricultural soils, longer-term adaptation strategies for soil management are needed to build adaptive capacity and to be able to endure environmental and production challenges that lie ahead. This research captures some of the bottom-up assessment that occurs on farms to inform their decision-making, but future research still has more to uncover in the relationship of soil management and broader adaptive strategies for sustainable agriculture.

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Chapter 4 From the Household to Watershed: A cross-scale analysis of residential intention to adopt Green Stormwater Infrastructure

4 Abstract

Improved stormwater management for the protection of water resources requires bottom-up stewardship from landowners, including adoption of Green Stormwater Infrastructure (GSI). More research is needed to identify the influence of interacting spatial, social, and physical factors on the intention to adopt GSI across a complex social-ecological landscape. We use a statewide survey of Vermont paired a cross-scale and spatial analysis to evaluate how residential intention to adopt for three different GSI practices (infiltration trenches, diversion of roof runoff, and rain gardens) varies with barriers to adoption, and household attributes across varying stormwater contexts from the household to watershed scale. Private landowners, who may be motivated more by on-site household and neighborhood experiences, may gravitate toward practices like infiltration trenches, while other practices, like rain gardens, may be perceived to serve stormwater function at larger extents, and diversion of roof runoff may be a part of a larger assembly of green behaviors. Improved stormwater management outcomes at the watershed and local levels depend on an adaptive approach that can adjust strategies along the rural-urban gradient, across the bio-physical landscape, and according to varying norms and institutional arrangements.

4.1 Introduction

4.1.1 The challenge of stormwater management

Worldwide, altered hydrology and eutrophication threaten freshwater resources (Carpenter et al., 2011). In the United States, 53% of the assessed rivers and streams, 70% of assessed lakes, reservoirs and ponds, and 79% of the assessed bays and estuaries were impaired for meeting "designated uses" including supporting drinking water supply, supporting aquatic life, and recreation (US EPA, n.d.). Many of these waterbodies' impairments are attributed to consequences of development in urban and rural landscapes including modified hydrology, habitat alteration, and point and nonpoint source pollution (US EPA, n.d.; Wear et al., 1998; Wemple et al., 2017). Ineffective stormwater management can cause increases in runoff rates and volumes, downstream flooding, stream bank erosion, increased turbidity, habitat loss, sewage spills, infrastructure damage, and transport of pollutants that contaminate receiving waters (Arnold Jr and Gibbons, 1996; UNEP, 2014; US EPA, n.d.). The ability to effectively manage stormwater is complicated interactions of multiple hydrological, biophysical, infrastructural, social, and demographic factors that contribute to runoff and pollution (Ahiablame et al., 2013; Pfeifer and Bennett, 2011; Wright et al., 2016; Zhang et al., 2015)

4.1.2 Green stormwater infrastructure

Green stormwater infrastructure (GSI) aims to mimic natural ecosystem functions to provide water storage and water quality regulation by promoting infiltration and evapotranspiration using vegetation, soils, and other elements (UNEP, 2014; US EPA, 2015). On-site treatment such as GSI or Low Impact Development (LID) offers cost-effective alternatives that may be integrated with existing conveyance stormwater systems in a variety of lot sizes and landscapes ranging from highly urbanized to sparsely developed to provide provisioning and regulating ecosystem services from the local to watershed scales (Pagella and Sinclair, 2014; Qiu and Turner, 2013; UNEP, 2014; U.S. EPA, 2000). GSI includes a variety of practices such as bioretention, pervious pavement, green roofs, tree box filters, infiltration trenches, rain barrels, and constructed wetlands, to slow runoff and treat pollutants including sediment, nutrients, bacteria, and heavy metals (Dietz, 2007; Hathaway and Hunt, 2007; UNEP, 2014; UNH, 2012; US EPA, 2015). As described by UNEP (2014), green infrastructure including grassed bio-swales, riparian buffers, and floodplain and wetland restorations that extends beyond urban stormwater contexts, provides multiple ecosystem services and water management benefits. Additional direct and indirect ecosystem services from GSI can include erosion control, temperature control, carbon sequestration, pollinator habitat, food production, as well as aesthetic, recreational, cultural, and social benefits (Dietz, 2007; UNEP, 2014; U.S. EPA, 2000; US EPA, 2015). Effectiveness of GSI and its potential for secondary benefits depends on the specific practice implemented and the surrounding context.

4.1.3 Engaging households and neighborhoods in stormwater management

The challenge of stormwater management and the need for decentralized approaches like GSI invites engagement from citizens, residents, and property owners (Brown et al., 2016; Green et al., 2012). Kollmuss and Agyeman (2002) present a useful categorization of the multiple factors that can influence pro-environmental behavior including external, internal, and demographic factors. For example, relationships with municipal governments can differ between urban and rural settings and could impact residential willingness to adopt GSI (Barbosa et al., 2012). At the household and neighborhood scales, several studies illustrate some of the tradeoffs and program challenges to different strategies for garnering support for improved stormwater management and promoting adoption of GSI (Ando and Freitas, 2011; Brown et al., 2016; Carter and Fowler, 2008). For example, Brown et al. (2016) found financial incentives and personal benefits to be enhance adoption of at-source stormwater management in a retrofit program. Carter and Fowler's (2008) study of subsidy and incentive programs for on-site stormwater management and green roofs across the United States point to tradeoffs between political will, cost of construction, and the ability to effectively target optimal sites for environmental benefit.

In a survey of two Syracuse, New York neighborhoods, Baptiste et al. (2015) found that efficacy, aesthetics, and cost were key factors influencing household willingness to implement GSI; and that some demographic differences, such as neighborhood, influenced the importance of these factors. The same study found that relatively high levels of GSI knowledge did not differ by demographic variables, and cited "lived experience" of combined sewer overflows and their negative impacts to be potential drivers of willingness to adopt (Baptiste et al., 2015; Baptiste, 2014). These experiences increased knowledge of the stormwater problem in general; however, the ability of environmental awareness to motivate behavior change is complex, with many of today's environmental challenges being slow to evolve and not perceived to demand immediate response (Kollmuss & Agyeman, 2002). Crisostomo et al. (2014) also found that "intangible benefits" including broad environmental, "green" benefits may be more motivating to homeowners than GSI as strictly a stormwater management strategy.

4.1.4 Tackling s**tormwater management across municipal and watershed scales**

Despite the useful frameworks and potentially practical management contexts provided by spatial, hydrological, and political, boundaries, water governance problems are fundamentally transboundary (Cash et al., 2006; Cohen and Davidson, 2011; Moss and Newig, 2010; Susskind and Islam, 2012). Residential level engagement in management of GSI, whether at the watershed or municipal scale, depends on various hydrological, political, social, spatial, and demographic factors (Chang, 2010; Cohen and Davidson, 2011; Griffin, 1999; Hopkins et al., 2014; Pfeifer and Bennett, 2011). While watershed delineations are useful for hydrologic and water quality analysis, governance and coordinated implementation at the watershed scale faces technical, institutional, and perceptual barriers including uncertainty around effectiveness, insufficient capacity, and fragmentation of multi-jurisdictional efforts (Baptiste et al., 2015; Cohen and Davidson, 2011; Roy et al., 2008).

At the municipal level, implementation of stormwater utilities and fees may be vulnerable to political pressure (Keeley et al., 2013). One major policy tool in the United States through the National Pollutant Discharge Elimination System (NPDES) program is the permitting of Municipal Separate Storm Sewer Systems (MS4) (OW US EPA, n.d.).

Since 1990, 750 Phase I MS4 permits were issued in urbanized areas with populations of 100,000; since 1999, 6,700 Phase II MS4 permits were issued to small municipal systems inside and outside of urbanized areas (OW US EPA, n.d.)(US EPA, 2017). Required permits for municipal stormwater and wastewater discharges can be important motivators for managing stormwater, potentially with GSI (Copeland, 2016; Fowler et al., 2013, 2013).

Multiple studies demonstrate decentralized GSI outcomes depend on hydrological, institutional, and demographic factors (Ahiablame et al., 2013; Barbosa et al., 2012; Pfeifer and Bennett, 2011; Roy et al., 2008; Wright et al., 2016; Zhang et al., 2015). But research is needed to identify the how interactions between spatial, social, and physical factors influence adoption of GSI across a complex social-ecological landscape in promoting sustainable water resource management (Chowdhury, Roy et al., 2011; Ostrom and Cox, 2010). We use a statewide survey of Vermont to evaluate how residential intention to adopt three GSI practices varies with different barriers to adoption, demographics, and multi-scalar stormwater contexts. Specifically, we study intention to adopt GSI within cross-scale stormwater contexts of exposure to site-level runoff, erosion, or flooding, perception of neighborhood-level challenges, town-level stormwater regulation, and watershed impairment in both rural and urban landscapes (Figure 1). This research reveals arrangements of biophysical, social, and institutional factors for GSI adoption that need consideration in promoting sustainable water resource management in a complex social-ecological system (Ostrom and Cox, 2010).

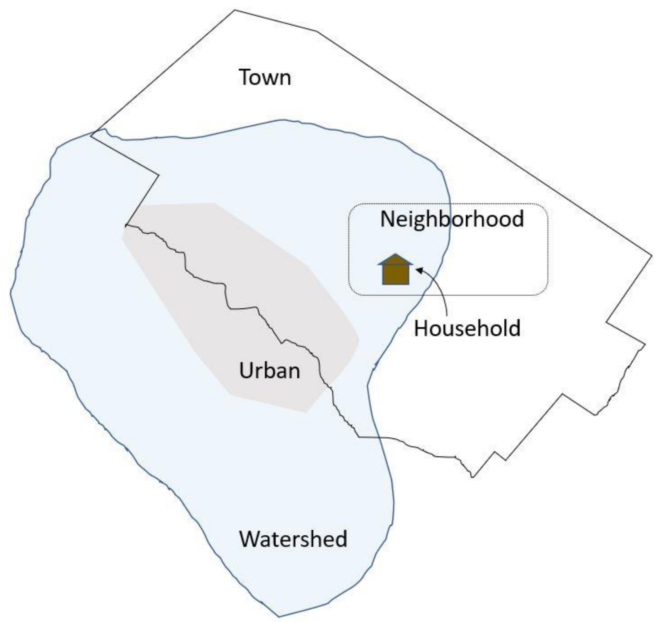


Figure 4-1. Conceptual Diagram of multiple watershed, town, development, and neighborhood scales potentially influencing household-site adoption of GSI. Decentralized GSI also occurs within multiple boundaries for stormwater management that can influence outcomes at various scales.

4.1.5 Challenges for Vermont

The state of Vermont is actively engaged in a series of initiatives related to nutrient pollution for its major basins including Lake Champlain, Lake Memphremagog, and the Connecticut River, all of which are transboundary, crossing state and/or national boundaries VT DEC, 2017). Multiple sources contribute to pollution of these waters, including stormwater and wastewater, agriculture, forests, and floodplains and riparian land (State of Vermont, 2015). The responsibility for clean-up is shared between federal, state, and local governments, the International Joint Commission, non-governmental organizations, landowners, concerned citizens, the private sector, and interest groups

(Coleman et al., 2017; Koliba et al., 2014). The 2016 Total Maximum Daily Load for Vermont's portion of Lake Champlain illustrates the challenge of improving water quality related to nutrient pollution in that this plan "will require new and increased efforts from nearly every sector of society, including state government, municipalities, farmers, developers, businesses and homeowners" (State of Vermont, 2015, p. 2).

4.2 Methods:

The Castleton Polling Institute administered a statewide survey entitled "Green Infrastructure Survey for Vermont Residential Properties" to Vermont residents in the summer of 2015. Survey questions addressed demographics, watershed and stormwater experience, adoption of or intention to adopt specific GSI practices, and barriers to adoption. (The survey can be found in Supplementary Materials I). This study extends beyond urban and suburban settings within which most stormwater research takes place and allows for spatial analysis across different household, social, spatial, political, and watershed dimensions of stormwater management. Respondents were asked about current adoption and intention to adopt seven GSI practices: actively divert roof runoff to a rain barrel or to lawn or garden instead of to street/sewer (henceforth referred to "diversion of roof runoff"), rain gardens, permeable pavement, infiltration trenches, tree box filters, constructed wetlands, and green roofs.

4.2.1 Survey Design

A probability based, address-based sample of Vermont was used for survey dissemination, based on the U.S. Postal Service's Delivery Sequence File. The sample was purchased from ASDE Survey Sampler, Inc. Each addressee was mailed a pre-notification letter, a survey packet (including a cover letter, the survey booklet, and a postage-paid, addressed business-reply envelope) and, separately, a reminder postcard. The top of the survey booklet instructed respondents to have the primary decision maker in the household complete the survey. When the response rate is adjusted to account for the survey returned undeliverable, the response rate is 16.5% for the final, completed surveys. The 577 non-pilot surveys were weighted to the 2014 U.S. Census American Community Survey population projections. The data were adjusted for the base probability of selection, sample level nonresponse, as well as post-stratification weights based on region. The post-stratification weights are based on three geographic regions of Vermont. (Supplementary Materials II) for a description of each region. No adjustments were made for the design effects due to weighting or clustering. The map (Figure 2) showing locations of survey recipients and those who completed the survey depicts a representative sample population.

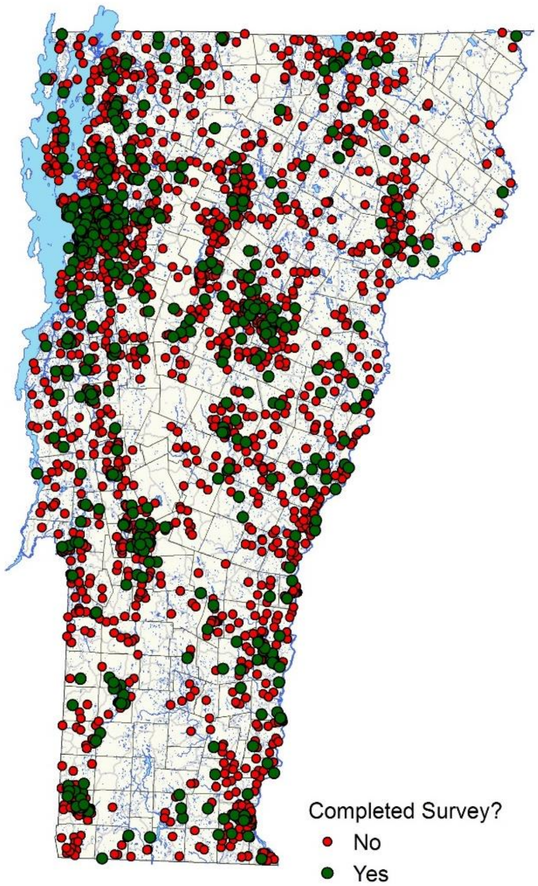


Figure 4-2. Map showing distribution of completed surveys (green) and nonresponses (red)

4.2.2 Data Analysis

Data points nested within multiple spatial contexts (e.g. neighborhood, town, and watershed) (Figure 1) were derived from both the survey and spatial analysis. Information about experience of site-level as well as perception of neighborhood stormwater and flooding problems, and town location was derived from the survey. Addresses were geolocated to measure proximity to water bodies and place households in larger stormwater management contexts including population, urban classification, and watershed scale.

4.2.2.1 Geocoded survey responses:

To evaluate how residential intention to adopt for three different GSI practices varies with barriers to adoption and household attributes across stormwater contexts, the survey data included addresses that was geo-located for spatial analysis. Where possible, respondent addresses were geo-located using Vermont's E911 road address range geocoder (VCGI, 2016). Geo-location of four hundred seventy (470) surveys allowed the cross-referencing of responses with spatial variables including proximity to water, urban zones, and residence in impaired watersheds. One hundred and seven (107) survey response addresses were PO Boxes and could not be geo-located to the exact residence, impeding analysis beyond the survey data.

Household proximity to water was defined as the closest distance from the residence to a body of water as measured using the Vermont Hydrography spatial layers of streams and rivers (order 4 and higher), lakes and ponds (U.S. Geological Survey et al., 2010). The American Community Survey (2015) was used to geolocate respondents in urban areas and clusters (coded as urban for analysis) as well as the population of census tracts (US Census Bureau, 2015; Supplementary Materials III). For the sub-basin level of analysis, streams and rivers that were listed on the 2014 303(d) list (VT DEC, 2016), as being impaired attributed to stormwater and development, were mapped; and the length of impairment of water bodies per HUC12 watershed was summed for each respondent. (See Supplementary Materials III for pollutant sources attributed to stormwater and development.) One hundred and four segments were included in the final development-related stormwater impairment classification spanning twenty-seven HUC12 watersheds in Vermont.

4.2.2.2 Household attributes, barriers to adoption and intention to adopt GSI

The survey asked questions about social and physical attributes of respondent residence and surroundings, current adoption of GSI, and the intention to adopt GSI practices. Survey respondents reported whether they had experienced one or more of the following residential stormwater and flooding problems: basement flooding, flooding of property, washout of lawns, and washout and erosion of driveway or road to house. In addition, the survey asked if they believed stormwater or flooding to be a problem in the respondent's neighborhood. Survey respondents were also analyzed for residence in one of Vermont's 12 Phase II Small MS4 towns using the respondents' town of residence from the survey responses (as opposed to geo-located data) (VT DEC, n.d.).

Both physical and social household-level information were collected including lot size, estimated imperviousness, type of residence, tenure, income, education level, and age. Respondents also answered questions about landscape management including whether they made decisions for property, use of compost or fertilizer. The survey also included "yes or no' questions about ten barriers to adoption for five of the GSI practices; constructed wetlands and green roofs were excluded. The factors included were: "not enough space," "costs too much," "no interest," "don't believe it works," "too much upkeep," "no need," "against property rules," "doesn't look good," "not suitable on my property," and "not enough information to decide". The percent of respondents reporting barriers to adoption for each practice was measured. Differences of barriers to adoption of rain gardens between households in MS4 communities and non MS4 communities were compared using paired T-tests.

Overall intention to adopt GSI assesses whether respondents are “likely” to implement one or more practices. A survey question asked about intention to adopt on a scale of 0-5 (with 0 meaning unlikely and 5 meaning highly likely) For each practice, scores of 3 through 5 were given a “1” and all values less than 3 a “0”. Respondents reporting adoption of the GSI practices were not included in the variable of intention to adopt. To assess intention to adopt across all the seven practices surveyed, the values were summed. Respondents who were likely to adopt one or more GSI practice were given a “1” and respondents with no intention were given a “0”.

Differences in overall intention to adopt between five spatial extents (Figure 1) were compared using paired T-tests for initial analysis. In addition, separate binary logistic regression models were run to determine spatial predictors and demographic determinants for overall intention to adopt GSI practices as well as for diversion of roof runoff, rain gardens, and infiltration trenches. For these four dependent variables, two models were analyzed here. The first set of independent variables included the seven spatial predictors. In the second run, only the independent variables that were significant from two preliminary logistic regression models (household attributes and barriers to adoption) were included. Binary logistic regression analysis was conducted using SPSS Statistics 24 for Windows using the “ENTER” method for standard regression analyses (IBM Corp., 2016).

4.3 Results

4.3.1 Spatial and demographic attributes of households with respect to runoff-related problems

Of the households surveyed, 54% experienced at least one problem from erosion, flooding, washouts, or stormwater runoff at the site-level. About a third reported experiencing "runoff, erosion, or washouts of driveway or road to your house" and about a sixth reported experiencing "basement flooding." Even fewer, around a tenth, reported either "runoff, erosion, or washouts of lawns or gardens," or "flooding on property." Most households (85.2%) that did not experience on-site problems also did not perceive runoff or flooding to be a problem at the neighborhood scale. In contrast, over a third (35.3%) of households with on-site challenges also perceived stormwater and or flooding problems at the neighborhood-scale (Table 1). A greater proportion (69.4%) of households that experienced on-site challenges fell in non-urban areas, which likely reflects the higher frequency of reported runoff-related driveway and road problems. A one-way ANOVA tests also showed that households that experienced erosion, flooding, washouts, or stormwater runoff had smaller census tract populations and had less impaired stream length within the local watershed. This is counter to what might be expected; more households experienced water-related problems in watersheds with less designated stormwater-impaired waterways.

Some of the results confirm expected rural-urban differences. For example, lot size and estimated proportion of built area (imperviousness) are negatively correlated. Imperviousness and smaller lot size were associated with urban areas, towns with stormwater permits, and watersheds with stormwater-related impairment. Types of on-site residential water challenges also differed across lot size and proportional imperviousness. Imperviousness was positively correlated with reported “runoff, erosion, or washouts of lawns or gardens,” whereas larger (less impervious) lots were positively correlated with reported “runoff, erosion, or washouts of driveway or road to your house.” “Basement flooding,” was more likely to occur in urban areas. Ownership, single-family residences, and decision-making about landscaping, were negatively associated with imperviousness, urban residence, towns with MS4 permits, and level of watershed impairment. Single family residences were more likely than other types of residences to report making their own decisions about their property and reported comparatively higher incomes. Interestingly, use of compost was positively correlated with education level, and was negatively correlated to imperviousness (See Supplementary Materials IV).

Table 4-1. Descriptive Statistics for the variables related to stormwater challenges at different spatial levels.

	Spatial Variables	Percent%	Mean	Std. Dev	Median	Min	Max
Household							
Survey	Flooding on property	9.91		0.30	0.00		
	Basement flooding	16.99		0.38	0.00		
	Runoff, erosion, and washouts of driveway or road to your house	32.18		0.47	0.00		
	Runoff, erosion, or washouts of lawns or gardens	11.77		0.32	0.00		
	Household "Problem"	54.19		0.50	1.00		
Geolocated	Proximity to water (meters)		374.57	291.50	314.5	13	2031
Neighborhood							
Survey	Stormwater problem in neighborhood	20.50		0.40	0.00		
	Flooding problem in neighborhood	14.06		0.35	0.00		
	Neighborhood Stormwater and/or Flooding problem	25.88		0.44	0.00		
Population and Urban							
Geolocated	Census Tract Population (1000)		4.06	1.67	3.84	0.91	9.05
	Census Urban clusters and areas	36.29		0.48	0.00		
Town							
Survey	Town has MS4 permit	24.88		0.43	0.00		
Watershed							
Geolocated	Development impairment/Watershed (1000 m)		4.28	7.92	0.00	0.00	30.33

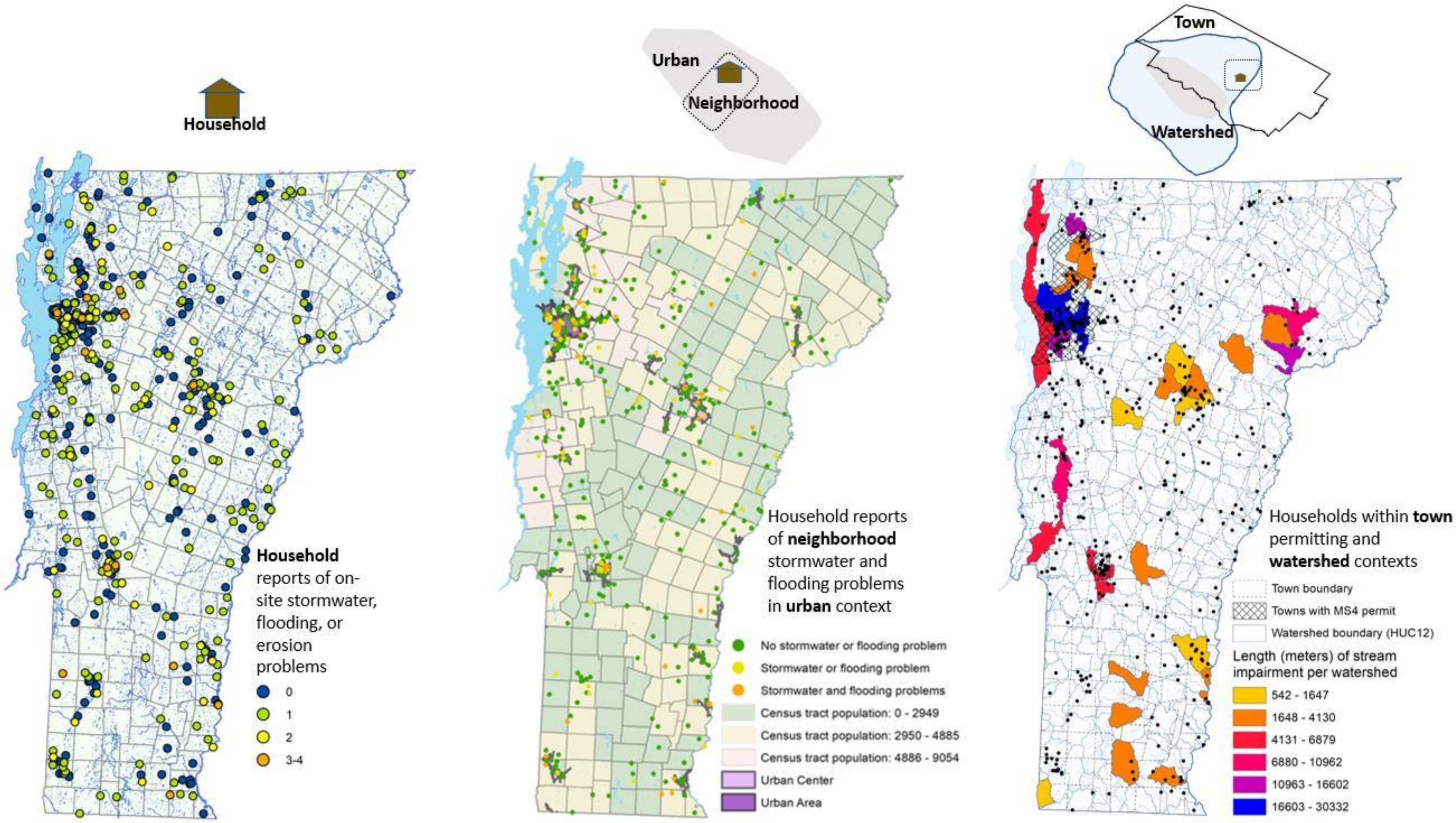
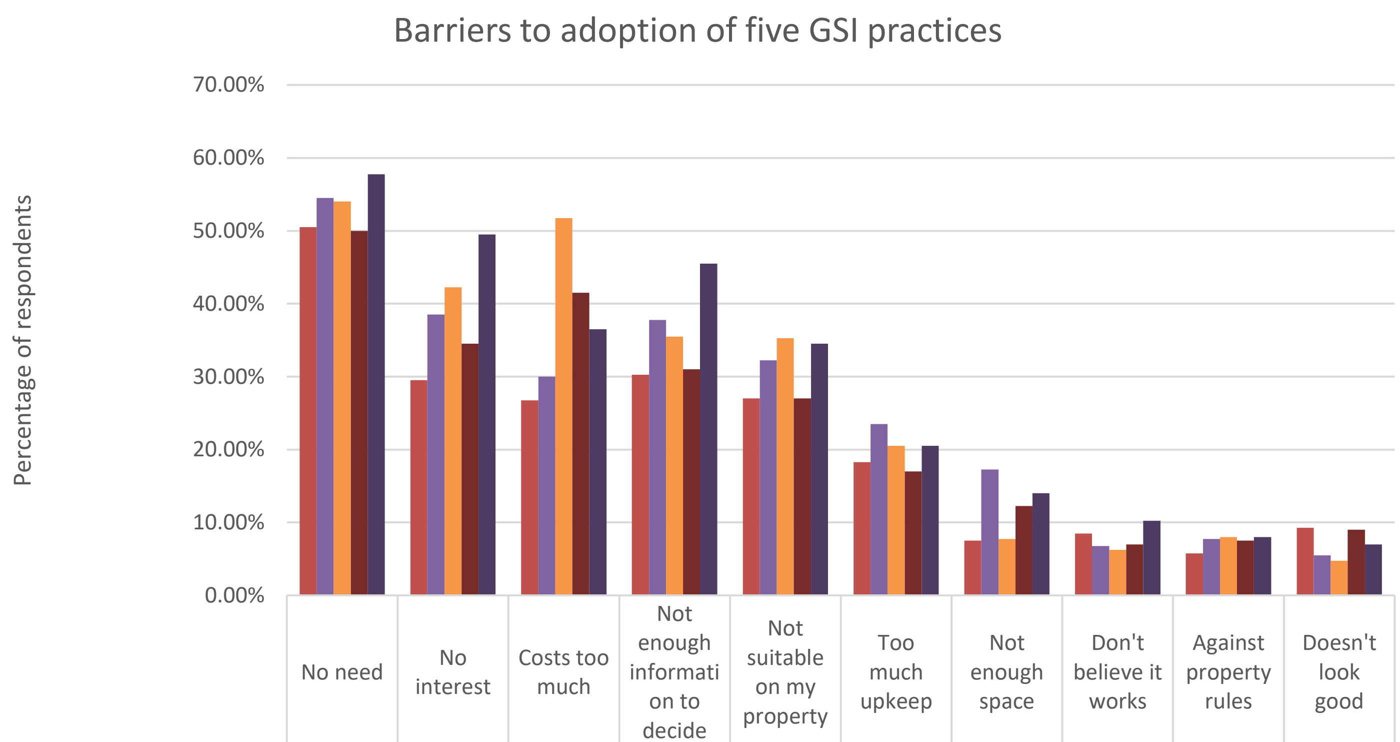


Figure 4-3. Concept diagrams and maps showing spatial distribution of stormwater related challenges from the household (site-scale) to watershed level for geolocated survey respondents. The left column map shows geolocated households colored by number of on-site stormwater, flooding, or erosion problems experienced in the last three years from the survey, with the

hydrography spatial layers that were used to measure proximity to streams and rivers (order 4 and higher), and lakes and ponds (U.S. Geological Survey et al., 2010). The center column map shows geolocated households that did not perceive stormwater or flooding to be a problem (green dots), perceived stormwater or flooding to be a problem (yellow dots), and perceived both stormwater and flooding to be a problem (orange dots) in the neighborhood over the last three years. Household perception of neighborhood stormwater and flooding problems is shown in the center map in the context of Census tract population and Urban Center and Urban Area designation using the 2015 US Census. In the right column map, survey respondents are geolocated in town and HUC12 watershed contexts. Towns with MS4 permits and watersheds with varying length of steam impairment are shown.

4.3.2 Barriers to adoption of GSI across spatial boundaries

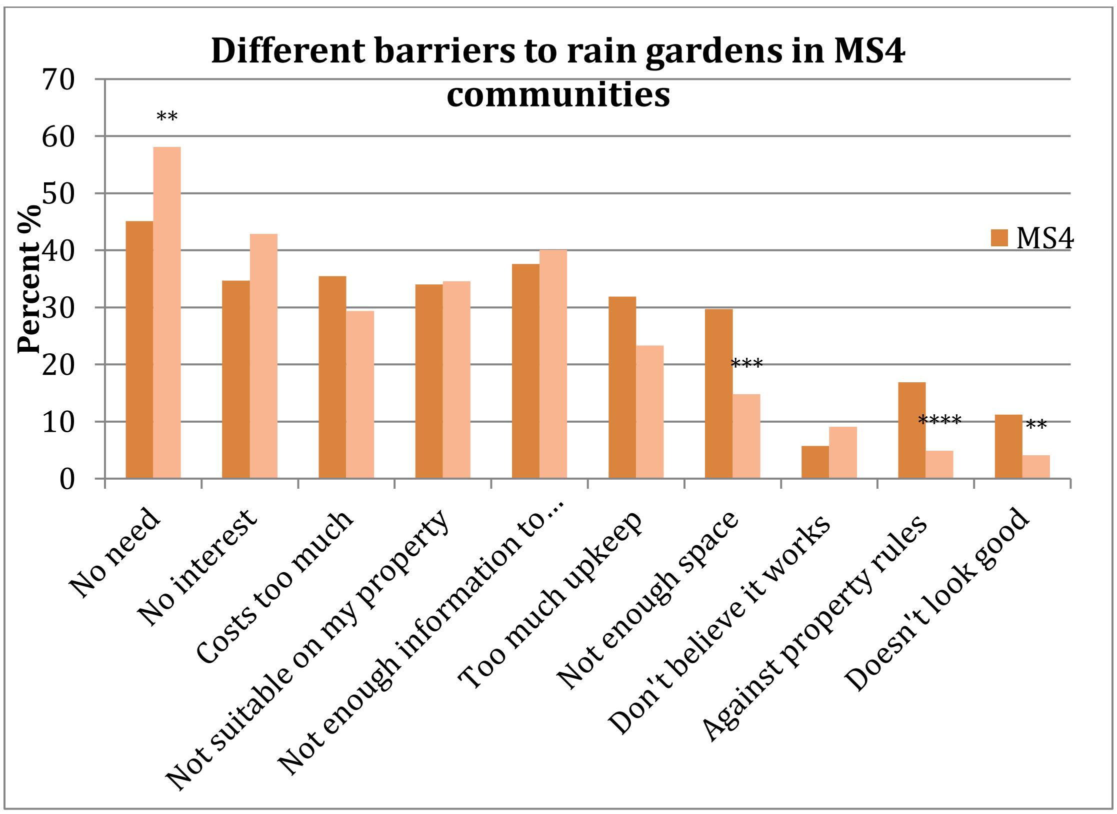
For five GSI practices, survey respondents indicated their perceptions of a list of barriers to practice implementation. Over half of respondents reported “no need” across the five practices. “No interest,” “costs too much,” and “not enough information to decide” followed (Figure 4). Fewer than 10%, reported that “doesn’t look good” was a barrier to adoption of the five GSI practices. In general, perceptions about the barriers were similar, but there were some notable differences in the barriers among the specific practices. For example, significantly more respondents reported the barrier “costs too much” for permeable pavers compared to the other practices surveyed. For rain gardens, permeable pavers, and tree box filters, more respondents report “not enough information to decide,” while lack of information was less likely to be indicated for diversion of roof runoff and infiltration trenches. The barriers “too much upkeep” and “not enough space” were reported for rain gardens significantly more than diversion of roof runoff and infiltration trenches. Significantly fewer respondents reported “doesn’t look good” to be a barrier for rain gardens and permeable pavers than the other practices.



	No need	No interest	Costs too much	Not enough informati on to decide	Not suitable on my property	Too much upkeep	Not enough space	Don't believe it works	Against property rules	Doesn't look good
Diversion of roof runoff	50.50%	29.50%	26.75%	30.25%	27.00%	18.25%	7.50%	8.50%	5.75%	9.25%
Rain garden	54.50%	38.50%	30.00%	37.75%	32.25%	23.50%	17.25%	6.75%	7.75%	5.50%
Permeable pavers	54.00%	42.25%	51.75%	35.50%	35.25%	20.50%	7.75%	6.25%	8.00%	4.75%
Infiltration trenches	50.00%	34.50%	41.50%	31.00%	27.00%	17.00%	12.25%	7.00%	7.50%	9.00%
Tree box filters	57.75%	49.50%	36.50%	45.50%	34.50%	20.50%	14.00%	10.25%	8.00%	7.00%

Figure 4-4. Percentage of survey respondents reporting ten barriers to adoption included in survey for each of the five GSI practices: Diversion of roof runoff, rain gardens, permeable pavers, infiltration trenches, and tree box filters.

Perceived barriers to adoption likely depend on the specific practice as well as other contextual factors. As one example, Figure 5 shows differences between barriers to adoption of rain gardens from towns with and without MS4 permits. There are differences in the frequency of respondents reporting “no need,” “not enough space,” “against property rules,” and “doesn’t look good.” While fewer respondents from MS4 communities reported “no need,” a relatively greater number of respondents from MS4 communities answered, “not enough space,” against property rules,” and “doesn’t look good.”



* P≤.10 **P ≤.05, ***P ≤.01, **** P≤.001

Figure 4-5. Percent of respondents reporting 10 barriers to adoption from MS4 and non-MS4 communities. Significant differences between groups are shown with an *.

4.3.3 Intention to adopt and adoption of GSI practices

Adoption of GSI and intention to adopt varied across the seven different practices including green roofs and constructed wetlands. In general, 65% of the survey respondents had either adopted or intended to adopt at least one of the listed GSI practices. 57% of the survey respondents reported no adoption of GSI practices, 28% had adopted one GSI practice, and 11% reported having two GSI practices at their residence. About two-thirds (68%) of the survey respondents reported little likelihood to adopt any of the listed GSI practices. About 16% and 8% of the survey respondents reported intention to adopt one or two GSI practices, respectively, in the next three years. "Diversion of roof runoff" was the most frequently reported practice for both adoption of GSI and intention to adopt. Infiltration trenches followed in current adoption, but did not differ significantly from rain gardens or permeable pavers for intention to adopt. The remaining practices (tree box filters, green roofs, and constructed wetlands) had significantly lower levels of both adoption and intention to adopt. However, frequency of reported current adoption of rain gardens and constructed wetlands did not significantly differ. Also, intention to adopt for infiltration trenches did not significantly differ from constructed wetlands (Figure 7).

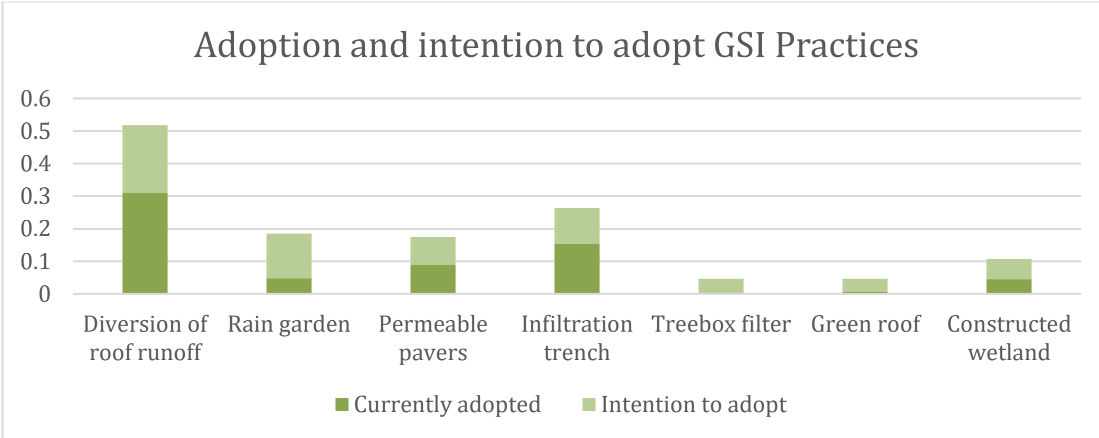


Figure 4-6. Proportion of survey respondents reporting adoption and intention to adopt the seven surveyed GSI practices.

4.3.4 Implementation of GSI and intention to adopt

Intention to adopt one or more GSI practice was evaluated in the context of different site, neighborhood, "community," town, and watershed scales of stormwater challenges. Figure 8 compares differences in intention to adopt one or more GSI practice among groups with varied types of risk and reported stormwater and flooding problems across spatial levels. A significantly greater proportion of the groups that experienced at least one problem related to water management at the household-site or the neighborhood-scale indicated intention to adopt one or more GSI practice regardless of whether the respondent was in a rural or urban area. There was no significant difference between level of intention to adopt GSI practices between groups in watersheds with stormwater-related impairment or in towns with MS4 permits.

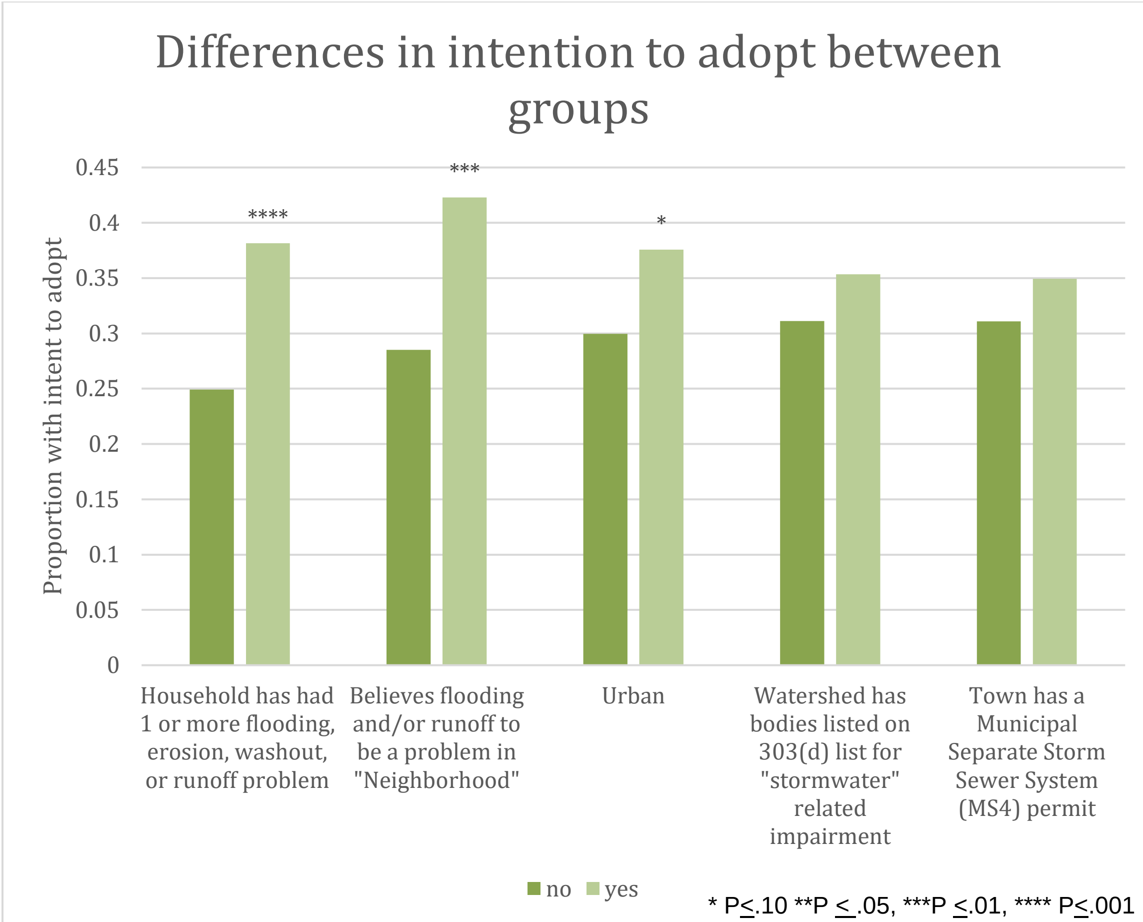


Figure 4-7. Differences in intention to adopt between spatial groups. Watershed variable was transformed to a binary variable for this figure.

Logistic regression was used to predict intention to adopt one or more GSI practices using the spatial variables and the demographic and management attributes. Using this method, experience and perception of stormwater and flooding problems at both the site and neighborhood-scale were significant predictors of intention to adopt one or more practice. Each of these spatial factors increased the odds of having intention to adopt by about 1.6 times. Intention to adopt also increased by 1.12 times with increases in population, and by 1.66 times with being in an urban area. When the additional demographic and socioeconomic variables were added to the model, experience of household-scale runoff management problems, population, and urban-ness remained significant spatial predictors to intention to adopt GSI. In addition, being situated in a watershed with stormwater-impaired streams had a slightly negative impact on intention to adopt, with residents in non-impaired watersheds being 1.05 times more likely to have intention to adopt. Younger respondents were more likely to have intention to adopt. Interestingly, respondents' reported use of compost increased the likelihood of having intention to adopt GSI practices by 1.923 times.

4.3.4.1 Diversion, rain gardens, trenches and intention to adopt

The three most commonly identified and well-suited practices to residential implementation in Vermont are diversion of roof runoff, rain gardens, and infiltration trenches. By predicting intention to adopt three GSI practices we see that the importance of the spatial, demographic, and barrier variables differ among practices. The spatial predictors of residence in urban areas and the experience of stormwater and flooding problems at the household-site increased likelihood of intention to adopt infiltration trenches by 2.88 and 2.28 times respectively. Residence in a HUC12 watershed that was not listed as impaired for development or stormwater also slightly increased the odds of having intention to adopt infiltration trenches (1.1 times). The spatial predictors for diversion of roof runoff and rain gardens also differed. For example, experience of household-site stormwater runoff and erosion, perception of neighborhood stormwater and flooding problems, and living in a more populated area increased the odds of having intention to adopt diversion of roof runoff. For rain gardens, the location of the residence in an MS4-permitted municipality as well as the perception of stormwater and flooding problems in the neighborhood were significant predictors of intention to adopt rain gardens. Residents of watersheds with less development-related impairment were slightly more likely to have intention to adopt rain gardens.

When the significant management and demographic variables and barriers to adoption were included in the model with the spatial variables, the patterns evolved. Household-site and neighborhood problems remained spatial predictors of intention to adopt infiltration trenches and of the demographic and barrier variables tested, “no need” was the only additional significant determinant. For diversion of roof runoff, only increasing population predicted intention to adopt and again, increased impairment within the watershed reduced likelihood of intention to adopt. Younger ages and use of compost were also significant social attributes increasing likelihood of intention to adopt this practice. There were four significant barriers: indication of “no interest,” “no need,” and “not suitable” reduced likelihood, whereas “don’t believe it works” increased the likelihood of having intention to adopt in the model. For rain gardens, residence in a MS4 community and having flooding or stormwater problems at the neighborhood-scale were significant predictors, and like diversion of roof runoff, less impairment within the watershed increased the likelihood of having intention to adopt. As expected “no need” and “no interest” were significant barriers whereas “against property rules” increased the likelihood of having intention to adopt rain garden (Table 2). In other words, people who said GSI was against property rules still wanted to adopt rain gardens.

Table 4-2. Logistic regression tables of intention to adopt for 4 dependent variables: Active diversion of roof runoff, rain gardens, infiltration trenches, and for at least one practice.

	Diversion of roof runoff: spatial predictors			Diversion of roof runoff: combined variables			Raingarden: spatial predictors			Raingarden: combined variables		
	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)
Proximity to water	0.000	0.550	1.000	0.001	0.318	1.001	0.000	0.511	1.000	-0.001	0.221	0.999
Population	0.151	0.066*	1.163	0.366	0.015**	1.442	-0.020	0.828	0.980	-0.111	0.434	0.895
Impairment length/HUC12 watershed	-0.007	0.777	0.993	-0.082	0.078*	0.921	-0.043	0.091*	0.958	-0.060	0.089*	0.942
Household-site runoff, erosion, washout problems	0.514	0.063*	1.672	0.501	0.246	1.650	0.164	0.594	1.178	-0.285	0.486	0.752
Consider stormwater/flooding a problem in neighborhood	0.696	0.02**	2.006	0.739	0.141	2.093	0.803	0.010**	2.231	0.943	0.040**	2.567
Urban	0.080	0.814	1.083	0.643	0.291	1.903	0.122	0.744	1.130	-0.547	0.302	0.579
Town has MS4 permit	0.181	0.687	1.198	-0.031	0.969	0.969	1.015	0.024**	2.759	1.699	0.013**	5.468
Age				-0.030	0.067*	0.971						
Female				-0.333	0.448	0.717				0.327	0.415	1.387
Rent										0.166	0.840	1.180
Compost				0.820	0.063*	2.271				0.390	0.383	1.477
No interest				-1.368	0.024**	0.255				-2.693	0.003***	0.068
Don’t believe it works				1.756	0.035**	5.790						
No need				-1.762	0.000***	0.172				-1.955	0.000***	0.142
Against property rules										2.788	0.006***	16.252
Not suitable on my property				-1.436	0.01**	0.238						
Constant	-1.903	0.000	0.149	0.074	0.951	1.077	-1.998	0.000	0.136	-0.332	0.664	0.717
-2 Log likelihood			350.397a			153.213a			319.391a			167.971[a]
Cox & Snell R Square			0.062			0.375			0.046			0.250
Nagelkerke R Square			0.085			0.503			0.078			0.393
Model Chi-sq			18.083			79.906			17.853			66.843
df			7.000			14.000			7.000			13.000
Sig			0.012			0.000			0.013			0.000

	Infiltration Trench: spatial predictors			Infiltration Trench: combined variables			GSI Practices: spatial predictors			GSI Practices: combined variables (without barriers)		
	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)
Proximity to water	0.001	0.316	1.001	0.000	0.550	1.000	0.000	0.614	1.000	-0.001	0.177	0.999
Population	0.030	0.803	1.030	-0.130	0.411	0.878	0.115	0.085*	1.122	0.136	0.063*	1.145
Impairment length/HUC12 watershed	-0.095	0.019*	0.909	-0.079	0.104	0.924	-0.031	0.105	0.969	-0.049	0.015**	0.952
Household-site runoff, erosion, washout problems	0.824	0.032**	2.279	0.834	0.071*	2.302	0.530	0.015**	1.699	0.640	0.007***	1.897
Consider stormwater/flooding a problem in neighborhood	0.570	0.126	1.768	1.218	0.008***	3.380	0.515	0.029**	1.674	0.415	0.105	1.515
Urban	1.057	0.012**	2.877	0.575	0.287	1.777	0.505	0.063*	1.657	0.531	0.07*	1.701
Town has MS4 permit	-0.161	0.765	0.852	-0.485	0.459	0.616	0.081	0.823	1.084	0.401	0.300	1.493
Age										-0.045	0.000***	0.956
Female												
Rent												
Compost										0.654	0.006***	1.923
No interest												
Don’t believe it works												
No need				-1.696	0.000***	0.183						
Against property rules												
Not suitable on my property												
Constant	-3.013	0.000	0.049	-1.518	0.048	0.219	-1.588	0.000	0.204	0.623	0.312	1.865
-2 Log likelihood			237.019a			161.078a			555.553a			476.508a
Cox & Snell R Square			0.064			0.143			0.049			0.136
Nagelkerke R Square			0.119			0.257			0.067			0.187
Model Chi-sq			22.201			37.656			22.527			60.563
df			7.000			8.000			7.000			9.000
Sig			0.002			0.000			0.002			0.000

4.4 Discussion:

4.4.1 Spatial and demographic attributes of households and barriers to adoption of GSI

The types of problems that respondents reported experiencing at the site-scale reflect the landscapes and topography of Vermont, where erosion of sediment in forested and mountain landscapes are common (Wemple et al., 2017). In more urban areas, capacity of stormwater infrastructure to manage flooding is more likely to be of concern (Barbosa et al., 2012). While the impacts of runoff from urban areas is well known, the impacts on water quality of erosion from unpaved roads in forested landscapes still needs more attention (Pechenick et al., 2014; Wemple et al., 2017; Wemple and Jones, 2003).

Analysis of the barriers that were reported for the different GSI practices raises additional questions about perception across different settings. Respondents reported more barriers to the adoption of tree box filters. This may be explained by tree box filters being traditionally implemented in more urban and densely impervious areas and in street right of ways (US EPA, 2015), while Vermont is still largely a rural state. The high frequency of responses of "no need" for the five practices (Figure 4) in the survey may also be reflective of more urban suited GSI practices among rural survey respondents. With a more rural audience experiencing problems at the site-scale in mind, the survey could have instead considered other practices related to GSI such as bio-swales, riparian buffers, wetland and forest restoration, reconnecting floodplains to rivers, flood bypasses, stone lined or vegetated ditches, bank stabilization, vegetated grass banks, and directing flow to retention areas (UNEP, 2014; U.S. EPA, 2000; US EPA, 2015; Wemple et al., 2017).

The barrier of "against property rules" was consistent across all the practices, but further investigation into different potential drivers of these rules, such as aesthetic norms or perceptions of upkeep, could help determine which GSI practices may be more appropriate for residential rental properties, homeowner associations, and other types of property management settings so that both owners and renters could realize benefits of GSI (Ando and Freitas, 2011; Fraser et al., 2013). The increased incidence of "doesn't look good" as a barrier to diversion of roof runoff, infiltration trenches, and tree box filters (Figure 4) highlights efforts to change aesthetic preferences may be needed (Goddard et al., 2013; Nassauer et al., 2009). Goddard et al. (2013) point to examples of changing neighborhood norms of lawn aesthetics to meet more ecological functions by influencing neighbors to follow early adopters. It is possible that changing aesthetic norms could also impact perceptions of upkeep and property rules. These barriers can be interdependent; the influence of removing one barrier can offset other barriers and influence implementation outcomes (Roy et al., 2008; Wilson and Dowlatabadi, 2007). While aesthetic standards and norms may hamper adoption of GSI and other ecological design elements for some households (Fraser et al., 2013; Goddard et al., 2013; Nassauer et al., 2009), adoption for others is also likely limited by income, tenure, and decision-making ability. In future research, ranking the different barriers to adoption could help understand the relative importance of each individual barrier (Roy et al., 2008; Steg and Vlek, 2009; Wilson and Dowlatabadi, 2007).

4.4.2 Residents' intentions to adopt Green Stormwater Infrastructure

Logistic regression of intention to adopt one or more GSI practice allowed for analysis of spatial and demographic determinants that are not necessarily specific to individual practices. The finding that the experience of one or more stormwater related problem at the household-site was a significant predictor of intention to adopt is important to improving stormwater management and builds on previous research studying household motivation to adopt of GSI (Baptiste, 2014; Baptiste et al., 2015). In the context of this study in Vermont, more rural residents indicated having experienced household-site problems. We see that in general the likelihood of intention to adopt one of the GSI practices listed increases with population size and urban-ness of residence. Given the known impacts of imperviousness and development on receiving waters, adoption of GSI in these settings could help to mitigate negative impacts (Arnold Jr and Gibbons, 1996). Further exploration into additional motivations for adoption by urban and suburban residence is therefore warranted, and underscores the need for increased outreach and education in these areas.

Given that in the coterminous United States, 39% of all houses exist in the "wildland-urban interface" with continued development pressure (Radeloff et al., 2005; Wear et al., 1998), a unique set of challenges for conservation, infrastructure, and water quality exists. The reported higher frequency of experiences of stormwater and erosion problems for households in rural areas also raises another important question about perceptual differences between rural and urban households as to what qualifies as "stormwater." For example, mismanaged stormwater can cause water runoff problems as well as water erosion, but the latter may not be as readily attributed to the concept of “stormwater management” in rural areas, dampening the perceived need for GSI or improved stormwater management. At the same time, Keeley et al. (2013) suggest that private landowners in urban areas may not perceive the management of stormwater to be something they are directly responsible for managing. Wilson and Dowlatabadi’s (2007) use of the term “embeddedness” to capture how choice and motivation can be constrained by an existing infrastructure and norm system that has accrued over time is applicable to stormwater. The status quo that relies on present infrastructure tends to be favored even if it is not optimal (Wilson and Dowlatabadi, 2007). In rural residential areas, the present infrastructure is more likely to be ditches and culverts than storm sewers, but stormwater still flows off roofs, driveways, and roads. Understanding perceptions around management of runoff and erosion due to stormwater from impervious surfaces would allow for a more nuanced strategy to address stormwater challenges with appropriate solutions in rural areas that are undergoing development, often with fewer restrictions related to zoning and master planning, and which may experience high rates of erosion and washouts.

This study also reveals some important demographic and management factors that may influence likelihood to adopt GSI practices that warrant further investigation. The findings that younger people may be more likely to intend to adopt and that the use of compost corresponds with likelihood of adoption of GSI could be important considerations in strategies promoting GSI; these relationships may signal a grouping of “green” behaviors by respondents (Ando and Freitas, 2011). Potential opportunities and risks need to be considered for coupling of GSI practices and other “green” behaviors for actual water quality and stormwater management improvement. For example, recent research calls attention to the risk of nutrient leaching from compost incorporated into the soil media of saturated soils including bioretention cells (Hurley et al., 2017). Target outreach and education materials may be needed for motivated adopters of “green” behaviors.

4.4.3 Different determinants of intention to adopt among diversion, infiltration trenches, and rain gardens

The results of the logistic regression models predicting intention to adopt suggests that across a complex landscape of multiple-level stormwater problems, individuals’ perceptions and intentions may depend on the specific practice. For example, infiltration trenches may be considered a more appropriate GSI practice for addressing site-scale stormwater runoff and erosion problems. When demographic and barrier predictors were added, “no need” was the only additional significant variable in addition to experience of household and neighborhood-scale stormwater problems, again implying a focus on utility or “need” of infiltration trenches in predicting intention to adopt.

The logistic regression model predicting intention to adopt diversion of roof runoff is more complicated. When the demographic attributes and barriers to adoption were included, population size was the predictive spatial variable, and age, compost use, and barriers such as “no need,” “not suitable,” “no interest,” and “don’t believe it works” also informed the model. The counter-intuitive effect of the barrier, “don’t believe it works” may reflect a perception of diversion of roof runoff as more of a “green” behavior with drivers beyond perceived utility and stormwater management. Ando and Freitas (2011) found adoption of rain barrels was not correlated with local levels of flooding, but instead in areas with higher incomes, near rain barrel distribution sites, and with lower levels of rentals. Intention to adopt may also have been motivated by additional co-benefits of diversion of roof runoff such as, rainwater harvesting for irrigation (US EPA, 2015). Interpretation of intention to adopt diversion of roof runoff is also complicated in that — as described in the survey— diversion could encompass somewhat different practices including disconnection of downspouts, routing water to lawns and gardens, and the use of rain barrels (US EPA, 2015). There was likely a perception among survey respondents that diversion of roof runoff would be the least costly of all practices listed in the survey even despite considerations of effectiveness. For example, Noppers et al. (2014) study of the purchase of electric cars demonstrate that weaker instrumental benefits can be superseded by symbolic and environmental motivators in the adoption of "green" behaviors.

The logistic regression model for rain gardens also portrays a different picture. In addition to perception of stormwater or flooding problems in the neighborhood, residence in an MS4 municipality also emerges as a significant predictor of intention to adopt rain gardens. This may be a signal of the different outreach and education efforts required as "minimum measures" in MS4 communities (VT DEC, n.d.). For example, Chittenden County Regional Planning Commission's (n.d.) "Rethink Runoff" campaign promotes disconnecting downspouts and use of rain barrels and rain gardens. Other GSI practices for which less educational information is available could be promoted in MS4 communities to encourage their adoption. While the importance of the barriers “no need” and “no interest” contributed to modeling rain gardens was similar to the other practices’, “against property rules” had an unexpected effect on intention to adopt rain gardens. Rain gardens were shown to be desirable despite the potential presence of the property rules barrier, suggesting rain gardens uniquely had appeal even for renters and owners that do not typically make their own landscaping decisions.

4.4.4 Limitations of residential green stormwater infrastructure study in a complex social-ecological landscape

This study surveyed the entire state of Vermont across a diverse set of rural, suburban and urban landscapes making some of the terms difficult to uniformly define and measure. For example, the term “neigbhorhood” likely invokes varying spatial areas and boundaries across different settings (Coulton et al., 2001), and some rural respondents did not identify with the term neighbhorhood. A separate challenge exists for the watershed level variable, in that the impairment measure depends on assessment and the listing procedure according to the statute of the 303(d) list (US EPA, n.d.), and may not uniformly capture all pollution and degradation tied to development and stormwater runoff across various landscapes (US EPA, n.d.). The use of this more narrowed definition limits understanding of how real watershed challenges impacts intention to adopt at the residential scale. In general, in interpreting these results, it is important to recall that the different spatial predictors were attributed using the survey data through questions about experience (site-scale) and perception (neighborhood-level), as well as geolocating the respondents and using external spatial and town level data (for urban, population, watershed impairment, MS4 status, and distance to water). For example, the survey did not ask respondents if they knew whether they lived in a town with an MS4 permit, or if their watershed was impaired for stormwater and development. While combining multiple data sources to address these types of research questions is common practice (Ando and Freitas, 2011), future research could investigate differences in perception, awareness, and risk factors as they relate to GSI practice implementation across different scales (Whitmarsh, 2008). These research directions also require a deeper understanding of respondents' knowledge of the distinct GSI practices surveyed. Although brief definitions of each practice were included in the survey, lack of familiarity with the practices may have influenced responses. Last, this study focuses on understanding different predictors of intention to adopt however we recognize that more attention is needed to understand the gap between stated intention and actual future adoption (Kollmuss and Agyeman, 2002).

4.4.5 Residential GSI practices from the household to the watershed

That motivation to adopt GSI can extend beyond stormwater function and environmental values is an important lesson for institutions like watershed organizations and local governments trying to leverage change to realize downstream benefits and engage private landowners. Crisostomo et al. (2014) found motivation to adopt GSI extended beyond stormwater management alone to intangible "green" benefits. In a study of low-carbon lifestyles, Howell (2013) shows the importance of altruistic values in predicting environmental behavior more than environmental values. Social marketing strategies that go beyond traditional educational interventions involved in public outreach could be helpful in leveraging the power of social norms iincluding the influence of neighbors and community members around stormwater management and GSI (Goddard et al., 2013; Kollmuss and Agyeman, 2002; Rosenberg and Margerum, 2008; Steg and Vlek, 2009). In this context, green stormwater infrastructure can serve a broader commitment to sustainability and integrative sustainability policies (Newell et al., 2012). Continued research is needed to explore planning strategies to realize adoption of GSI and promote desirable co-benefits of GSI practices across scales.

The need to tailor solutions to different institutional settings, is highlighted when considering the results that households in urban, MS4 permitted towns, with impaired watersheds, may have less decision-making ability to implement appropriate GSI practices. As the case of intention to adopt rain gardens demonstrates, evaluating barriers through different jurisdiction and management contexts may reveal opportunities to tailor interventions to motivations, capacities, and circumstance of different target groups, and identify how contextual factors may be affecting environmental behavior (Steg & Vlek, 2009). Developing strategies to promote appropriate GSI adoption for property owners is especially important when considering that the survey respondents report “against property rules” in some areas more than others (Figure 5). If GSI is “against rules” in MS4s significantly more than in non-MS4 communities, than that is a phenomenon that may need to be addressed as towns that are charged with increasing implementation of stormwater best management practices may look to private landowners (Thurston, 2006) to incorporate more GSI on their own properties. Ando and Freitas (2011) point out rain barrels may be appropriate in single family rentals, but permeable pavement, rain gardens, and green roofs may be more appropriate for larger multi-unit residences. As pressure to address stormwater management continues to increase targeting residential property owners to adopt GSI practices will be an important strategy. Programs to encourage investments by landlords in low-rise rental housing may need to be developed (Ando and Freitas, 2011). There is a need to be creative in looking to a complex social-ecological landscape to absorb and manage stormwater and encourage cross-scale benefits even in less traditional settings like on private land and along roads in rural developments.

4.5 Conclusion

Improved stormwater management outcomes at the watershed and local levels depend on an adaptive approach that can adjust strategies along the rural-urban gradient, across the bio-physical landscape, and according to varying norms and institutional arrangements. As stormwater management conditions vary at the site-scale across landscapes, stormwater best management practices need to be inclusive of multiple motivations across a complex social-ecological landscape. In this context, future management and research approaches need to account for varying dimensions of biophysical and social motivators of different green stormwater infrastructure practices from the household site to the watershed scale. While much of the GSI and LID literature focuses on implementation of best management practices in urban and suburban areas, some practices may provide needed mitigation of downstream erosion and sediment transport in rural areas while also addressing to site-specific challenges.

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Chapter 5 Conclusion

Bottom up adaptive management and stakeholder participation is essential to clean water and healthy soils. Environmental problems exist within a complex social ecological system, and solutions need to be able to be implemented effectively across scales, as well as account for uncertainty. Complex environmental challenges require multifunctional adaptive solutions. Agricultural soil health and residential green stormwater infrastructure are two examples of bottom-up, decision-maker driven systems that can provide multiple ecosystem services and share common principles; both can be managed or designed to address different bio-physical and social conditions and objectives. A commitment to a "learning by doing" approach (Walters, 1997) within and across scales is necessary in order to facilitate adaptation to change. Stakeholder participation is fundamental to supporting this approach and to allow for cross-scale knowledge exchange, elicit different ways of knowing, and to manage tradeoffs among values in identifying and implementing effective solutions for clean waters and healthy soils.

The research chapters in this dissertation studied bottom-up adaptive management and stakeholder dimensions that are essential to addressing complex environmental challenges, but there are many opportunities to go beyond the research presented here. Chapter 2 evaluated a participatory process to elicit solutions to address pollution in Lake Champlain Basin in the face of climate change. Stakeholder-generated solutions revealed adaptive solutions across domains and time horizons with varying levels of complexity for implementation. This forum was used both to increase creativity and establish legitimacy of potential solutions and reflected stakeholder perception and priority; there were important lessons learned. Participatory processes can be designed to engage stakeholder feedback to promote accountability regarding the research process, and improve outcomes across research, policy, and practice. Regardless of the specific method, stakeholder participation requires mechanisms to re-evaluate and support continued engagement as new knowledge and capacities develop and conditions change. In focusing on adaptive solutions, future research using participatory processes could evolve to focus on specific interventions, or include participatory mapping or modeling to augment pathways for knowledge coproduction.

Chapter 3 explored on-farm adaptive management through soil monitoring. The study makes a significant contribution in describing on-farm use of soil indicators to inform decision making, and linkages to adoption of best management practices. These findings point to underlying adaptive strategies that may influence soil management approaches, and a natural progression of this research would be to understand how these findings relate to broader management approaches, not exclusively focused on soil resources. While this study inherently seeks to examine whether farmers were engaged in adaptive management using bottom-up feedback from soil monitoring, the list of indicators was developed without direct farmer participation. Future studies would benefit by building from studies assessing farmer knowledge and engagement with soil health to take advantage of tacit farmer knowledge and contribute more contextual understanding. Similarly, future models could integrate dimensions of farmer learning in soil management to understand implications for adaptive capacity and provision of ecosystem services at a broader scale. Sustainable management of land resources fundamentally depends on landowner stewardship.

Last, Chapter 4 presented a cross-scale analysis of residential green stormwater infrastructure within a complex social-ecological landscape. This research highlights different strategies that can be used to address management challenges from site to watershed. Individual GSI practices can have varying biophysical and social motivators. Continued research about how green stormwater infrastructure solutions can address unique challenges and achieve different objectives across rural and urban landscapes is needed, as is improved understanding of how rural and urban areas may have different perceptions of and definitions of "stormwater."

Research informing science, policy, and practice needs to continue to pursue multiple dimensions of an "all-in approach" to address complex environmental problems affecting sustainable protection of water and soil resources. While this dissertation recognizes the importance of bottom-up adaptive management and stakeholder participation, there are opportunities for increased involvement throughout the research process including eliciting stakeholder input in design of data collection and analysis. This requires continued use of mixed methods and collaboration within academia and beyond to be positioned to pursue practical applications of research that can be communicated and integrated across a complex landscape. Most importantly, sustainable stewardship of soil and water resources depends on approaches across science, policy, and practice that embody a long-term commitment to adaptive management and stakeholder engagement.

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Appendix A Supplementary Materials for Chapter 2

List of participant generation interventions

Fifty-five participant generated interventions from the Spring 2014 CSS2CC.org online forum and multi-stakeholder workshop

BOLD = CRITICAL INTERVENTION

1. Regulate river corridors and floodplains at the regional scale to give rivers room to move and achieve stream equilibrium and flood plain function
2. **Expand regulations for municipalities and private landowners and require State highway facilities to use on-site runoff storage practices setting an example for municipalities and commercial sites. Require green stormwater infrastructure such as raingardens, bioretention and infiltration techniques to reduce and treat stormwater runoff on projects of a half-acre.**
3. Improve existing stormwater management practices for large and small construction projects and retrofit existing commercial and industrial sites with green stormwater infrastructure
4. Size culverts with up-to-date precipitation data to prevent washouts
5. Stop armoring and channelizing rivers and shorelines; restore previously armored areas and remove dams where possible
6. Create banking system for flood prevention funding
7. Develop a water quality mitigation bank allowing for trading among municipalities within a watershed to site best management practices at most beneficial locations
8. Develop statewide program to subsidize reducing nutrient sources and increase areas with water storage capacity on farmland for flood mitigation by incentivizing practices to increase soil organic matter on farms improving water storage and soil fertility
9. Give property tax incentives for enhanced stormwater management
10. Develop a hotline complaint system for construction runoff via state agency
11. Require runoff reduction practices for small farms and invest in inspection and enforcement of water quality regulation on all farms
12. Expand water quality monitoring in streams and lakes
13. Manage rivers to avoid flood impacts by identifying flood generation and attenuation zones across landscape
14. Increase funding for improvements at wastewater treatment plants
15. Upgrade waste water treatment facilities to be flood proof
16. Incentivize use of emerging eco-technologies for phosphorus capture and reuse from wastewater and stormwater

17. Require composting and increase recycling to reduce nutrient imports from outside the watershed, and to reduce landfill waste-stream and greenhouse gas emissions
18. **Develop market mechanisms and methods to reclaim phosphorus from farms, runoff, wastewater, and solid wastes**
19. Expand research on and use of low-fertilizer cropping strategies
20. **Tie agricultural incentives to the requirement of nutrient balancing on farms in nutrient management planning; manage manure spreading and fertilizer application practices. Include the requirement of practices such as cover cropping and no-till to reduce soil and nutrient loss from fields.**
21. Discourage imports of high-phosphorus fertilizers and animal feed from outside of the basin through a tax.
22. Target and employ erosion control measures on at-risk stream banks
23. **Require vegetated buffers in riparian zones and along lakeshores**
24. **Change zoning and land use and transportation policy mechanisms to require smart growth and low-impact development and prevent land parcelization to encourage ecosystem service provision**
25. **Invest in improving better road and backroads construction and maintenance practices**
26. Inventory transportation network and identify infrastructure in need of upgrade
27. Require development and zoning decisions to account for downstream impacts
28. Limit development in river corridors, including phasing out obsolete buildings in flood prone areas with policy and incentives
29. Incentivize pasture-based dairy, integrating feed and livestock production to improve fertilizer and manure loading and management
30. Amend exemptions for agriculture and forestry in law and tax policies including Current Use
31. Require livestock exclusion from streams
32. Enact a moratorium on wetland impacts and enhance functions of existing wetlands
33. Increase funding and participation in conservation easements to focus on sites with climate change adaptation and mitigation benefits and ensure compliance
34. Manage land use to protect and enhance terrestrial and aquatic wildlife habitat, including salmonid habitat
35. Require sustainable forestry practices and regulations, including maple stands for syrup production in BMP requirements.
36. Invest in bioremediation, phytoremediation, brownfields clean-up to reduce pollution and improve quality of existing developed areas
37. Use climate-resilient tree species for forestry and revegetation projects to enhance and maintain forest functions
38. Invest in research on refining sustainable forestry practices
39. Increase education about opportunities for mutual economic and ecological benefits and stewardship focused on Lake Champlain

40. Invest in research, education, and outreach for farm resilience in a changing climate
41. Employ market mechanisms to price and value farm products to reflect ecological impacts
42. **Provide more financial and technical assistance and outreach to promote soil health and associated best practices on farms**
43. Develop BMPs for soil health on vegetable and berry farms
44. Increase research on costs of agricultural best management practices (BMPs)
45. Expand monitoring and evaluation of effectiveness of water quality BMPs
46. Research relationship between land use, water quality, mitigation efforts, and climate change
47. Develop more streamlined and simpler stormwater manual
48. Develop required science curriculum about watershed concepts, and water quality impacts for local officials and on a supervisory union basis
49. Purchase lands along rivers to allow reforestation; provide grants for landscaping for lakeshores and river banks
50. Remove subsidies for flood insurance (especially new construction)
51. Establish on farm soil monitoring for farms and private landowners
52. Incentivize, use and enhance cross boundary collaborations across local, regional, and state institutions
53. Develop regulatory framework for onsite septic for phosphorus and nitrogen pollution decrease
54. Require continuing education for farmers
55. Web-based, real time, monitoring network to connect water quality outcomes to farm practice

Appendix B Supplementary Materials for Chapter 3

Supplementary Tables

Table 0-1 Mann Whitney U-test results between demographic variables and farmers that reported use (1) and no use (0) of soil indicators.

Use of Soil Indicator		Age (years)					Education					Net Income				
		median	mean rank (n)	u	z	p	median	mean rank (n)	u	z	p	median	mean rank (n)	u	z	p
Crop yield	0	5	42.4 (20)	638	-1.131	0.258	5	48.3 (20)	756	-0.037	0.97	2	43.53 (20)	660.5	-0.583	0.56
	1	5	50.11 (76)				5	48.55 (76)				2	47.33 (72)			
Quality of crop	0	5	46.47 (15)	577	-0.316	0.752	4	44.87 (15)	553	-0.567	0.571	2	35.4 (15)	411	-1.822	0.068*
	1	5	48.88 (81)				5	49.17 (81)				2	48.66 (77)			
Organic matter	0	5	44.78 (27)	831	-0.738	0.46	4	45.44 (27)	849	-0.587	0.557	1.79	33.23 (26)	513	-3.022	0.003***
	1	5	49.28 (68)				5	49.01 (68)				2	51.11 (65)			
Nutrient content: NPK	0	5	46 (26)	845	-0.551	0.582	4.08	48.79 (26)	902.5	-0.064	0.949	2	39.35 (26)	672	-1.67	0.095*
	1	5	49.43 (70)				5	48.39 (70)				2	49.32 (66)			
"Look and feel"	0	5	46.13 (27)	867.5	-0.536	0.592	4.43	47.5 (27)	904.5	-0.227	0.821	2	40.74 (27)	722	-1.38	0.168
	1	5	49.43 (69)				5	48.89 (69)				2	48.89 (65)			
Infiltration	0	4.99	39.26 (23)	627	-1.875	0.061*	5	50.17 (23)	801	-0.341	0.733	2	40.8 (22)	644.5	-1.189	0.234
	1	5	51.41 (73)				5	47.97 (73)				2	48.29 (70)			
Topsoil depth	0	5	38.43 (30)	688	-2.266	0.023**	5	46.3 (30)	924	-0.301	0.763	2	40.74 (27)	722	-1.17	0.242
	1	5	51.75 (64)				5	48.06 (64)				2	47.54 (63)			
Signs of erosion	0	5	43.13 (26)	770.5	-1.182	0.237	4	43.71 (26)	785.5	-1.058	0.29	2	35.24 (25)	556	-2.558	0.011**
	1	5	50.49 (70)				5	50.28 (70)				2	50.7 (67)			
Compaction	0	4	36.98 (26)	610.5	-2.458	0.014**	5	50.75 (26)	825.5	-0.616	0.538	2	42.65 (26)	758	-0.791	0.429
	1	5	52.15 (69)				5	46.96 (69)				2	47.34 (65)			
Soil moisture	0	5	45.67 (24)	796	-0.493	0.622	4.75	45.92 (24)	802	-0.441	0.659	2	39.72 (23)	637.5	-1.365	0.172
	1	5	48.79 (71)				5	48.7 (71)				2	48.13 (68)			
Soil pH	0	5	48.65 (17)	652	-0.11	0.913	4	40.91 (17)	542.7	-1.206	0.228	2	39.62 (17)	520.5	-1.143	0.253
	1	5	47.86 (78)				5	49.54 (78)				2	47.47 (74)			
Signs of life	0	5	45.67 (23)	774.5	-0.574	0.566	4	43.63 (22)	727.5	-0.991	0.322	2	39.48 (22)	615.5	-1.464	0.143
	1	5	49.39 (73)				5	50.03 (73)				2	48.71 (70)			
Disease and pests	0	5	44.23 (20)	674.5	-0.709	0.478	4	44.58 (20)	681.5	-0.645	0.519	2	36.61 (19)	505.5	-1.806	0.071*
	1	5	49.01 (75)				5	48.91 (75)				2	48.48 (72)			
Field history	0	4.63	39.93 (30)	733	-2.088	0.037**	4.93	49.4 (30)	963	-0.22	0.826	2	41.41 (29)	766	-1.283	0.199
	1	5	52.39 (66)				5	48.09 (66)				2	48.84 (63)			

Table 0-2 ANOVA table showing differences in values of Resilience, Transformation, and Resistance factor between different management and land use groups. Significant differences of <u><</u>0.05 are in bold. Cells in green show significantly greater reported importance of indicators for the group identified at the top of the table; the opposite is true for cells in red.

	"Certified Organic"			"Perennial only"			"Pasture"			"Hay"			"Annual crops"			"Row crops"			"Vegetable crops"		
	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.	1	0	Sig.
Resilience_Factor	0.105029	-0.01859	0.717	**-0.21902**	**0.43439**	**0.037****	0.277406	-0.03461	0.517	-0.76974	0.077006	0.103	**0.434398**	**-0.21902**	**0.037****	0.511665	-0.09419	0.149	0.370533	-0.08328	0.243
Transformation_Factor	-0.05952	0.011691	0.836	**-0.2162**	**0.42887**	**0.04****	0.155976	-0.01946	0.716	0.578564	-0.05788	0.224	**0.42887**	**-0.2162**	**0.04****	-0.0562	0.010049	0.876	**0.829822**	**-0.18651**	**0.007*****
Resistance_Factor	0.241207	-0.09757	0.321	0.03893	-0.07723	0.718	0.155976	0.027559	0.607	0.047947	-0.0048	0.92	-0.07723	0.03893	0.718	-0.30941	0.055324	0.386	0.11469	-0.02578	0.72

Table 0-3 ANOVA table showing differences in values of Resilience, Transformation, and Resistance factor between adopters and non-adopters of 2 practices: No-till and Conservation buffer. Significant differences between adopters and non-adopters are in BOLD.

		No-till					Conservation buffer				
		Sum of Squares	df	Mean Square	F	Sig.	Sum of Squares	df	Mean Square	F	Sig.
Resilience	Between Groups	3.206	1	3.206	3.305	0.076	0.000	1	0.000	0.000	0.993
	Within Groups	41.718	43	0.970			44.924	43	1.045		
	Total	44.924	44				44.924	44			
Transformation	Between Groups	3.799	1	3.799	3.972	0.053	0.503	1	0.503	0.487	0.489
	Within Groups	41.125	43	0.956			44.421	43	1.033		
	Total	44.924	44				44.924	44			
Resistance	Between Groups	0.025	1	0.025	0.024	0.878	0.018	1	0.018	0.017	0.896
	Within Groups	44.899	43	1.044			44.906	43	1.044		
	Total	44.924	44				44.924	44			

Farmer survey

ID___________________________

Thank you for taking the time to complete this survey. This survey is intended to be completed by Vermont Farmers. The goal of our research project is to work with farmers, agricultural service providers, researchers and community organizations to better understand which farming practices you use and how you choose them. Your input is extremely valuable to us! This survey should take 15-20 minutes to complete. It focuses on six key topics, including 1) farm characteristics; 2) farming practices; 3) how and why you make decisions on your farm; 4) nutrient management; 5) how weather and climate affect you; and 6) income and education information.

If you are not sure what a term or a practice means, please check the glossary at the end of the survey.

Your responses, name and identifying information will remain confidential.

Confidentiality statement
The information you provide will be used for statistical purposes only. In accordance with the Confidential Information Protection provisions of Title V, Subtitle A, Public Law 107-347 and other applicable Federal laws, your responses will be kept confidential and will not be disclosed in identifiable form to anyone other than employees or agents. By law, every employee and agent has taken an oath and is subject to a jail term, a fine, or both if he or she willfully discloses ANY identifiable information about you or your operation. Response is voluntary.

According to the Paperwork Reduction Act of 1995, an agency may not conduct or sponsor, and a person is not required to respond to, a collection of information unless it displays a valid OMB control number. The valid OMB number is 0535-0039. The time required to complete this information collection is estimated to average 15 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information.
End of confidentiality statement

Section 1: Please tell us about your farm

1. How many years have you been farming? _______________ years.

2. Land usage (in acres) for entire farm during the most recent growing season.

	Owned	**Leased**
Pasture		
Hay		
Row crops/small grains/corn		
Wetland		
Woodland pastured		
Woodland not pastured		
Vegetables/herbs		
Tree fruits		
Small fruits		
Fallow		
Other (farm buildings, roads, wasteland, etc.)		
TOTAL		

3. What bodies of water do you have on your property? (Please check all that apply)

No bodies of water on property		Intermittent streams	
Rivers		Vernal pools	
Streams		Ponds	
Creeks		Other (please describe)	

4. What agricultural goods generate income on your farm?

Product	**Approx. Percentage of Total Sales**	**Product**	**Approx. Percentage of Total Sales**
Vegetables		Dairy – cows	
Herbs		milkers	
Timber		heifers	
Maple Syrup		calves	
Grains for human consumption		bulls	
Grains for livestock feed		Dairy – sheep	
Hay		Dairy – goat	
Tree Fruit (raw, not processed)		Meat – beef	
Small Fruit (raw, not processed)		Meat – pork	
Value added fruit or vegetable products		Meat – chicken or other fowl	
Bedding plants		Meat – turkey	
Nursery Plants		Meat – Goat	
Christmas trees		Meat – lamb	
Sod		Wool – sheep	
Fluid Milk		Eggs – chickens or other fowl	
Dairy products (other than fluid milk)		Other (please describe)	

5. Management type (check all that apply)

Certified organic	
Organic, not certified	
Conventional	
Other (please describe below)	

Section 2: Please tell us about your farming practices

6. Which of the following practices do you currently implement on your farm? (check all that apply)

PRACTICE	Check if you use it
Hoop houses/high tunnels	
Green manures (crop residue incorporation into soil)	
Cover crops	
No till	
Timely manure incorporation	
Pest/disease management	
Invasive species management	
Irrigation (automated, drip, overhead)	
Conservation buffer strips (riparian buffers, wind breaks, stream corridors, buffer strips, shelter belts, hedgerows)	
Wetlands conservation	
Stormwater Runoff Management	
Drainage tile	
Rotational grazing	
Animal diversity	
Animal feed management	
Agroforestry (silvopasture, alley cropping, forest farming)	
Alternative energy (biomass, wind, solar, methane digesters)	
Reduced tillage (zone, strip, mulch, ridge)	
Wastewater Runoff Management (wastewater/washwater from barnyard, production area and silage bunker)	
Drainage ditches and diversions	
Nutrient management plan	
Insurance (farm policies, crop insurance, product liability)	

7. In the past year, have you noticed any on-farm soil or water resource problems that have negatively affected your agricultural operations? (Please check all that apply)

Poor drainage/soil saturation		Bank and Channel Erosion	
Potability		Excessive Runoff, Flooding, or Ponding	
Soil compaction		Drought	
Nutrient loss		Other (please describe)	
Sheet and Rill Erosion		None of the above	
Gully/Concentrated Flow Erosion			

Section 3: Please tell us about your use of conservation programs and practices

8. There are many different conservation practices that farmers use.

Suppose an agency offered to pay you to implement conservation practices on your farm for one year. Payments would be offered on a per acre basis. Conservation practices may be offered as singly or in groups. Which combination of practices would you be mostly likely to implement?

Consider each of the following combinations and rank them from 1 to 7, with 1 being the one you are most likely to choose, and 7 being the one you are least likely to choose. Use each number only once.

Please refer to the last page of this survey for definitions of conservation practices if needed.

CONSERVATION PRACTICES	**RANK (1-7)**
You will be paid $30/acre to implement conservation tillage.	
You will be paid $90/acre to implement cover cropping.	
You will be paid $105/acre to implement conservation buffers.	
You will be paid $120/acre to implement conservation tillage and cover cropping.	
You will be paid $170/acre to implement conservation buffers and conservation tillage.	
You will be paid $175/acre to implement cover crops and conservation buffer strips.	
You will be paid $205/acre to implement cover crops, conservation buffers and conservation tillage.	

9. Are you currently enrolled in any federal government conservation programs (check all that apply)? If you are not enrolled in any of these, skip to question 11.

Conservation Program	**Mark if applicable**	**What practices did you implement as a result of participation in this program?**	**Would you have used these practices without this program? (Y, N, Not sure)**
I am not enrolled in any federal government conservation programs.			Y____ N____ Not sure____
Wildlife Habitat Incentives Program (WHIP)			Y____ N____ Not sure____
Environmental Quality Incentive Program (EQIP)			Y____ N____ Not sure____
Conservation Reserve Enhancement Program (CREP)			Y____ N____ Not sure____
Farm and Ranch Lands Protection Program (FRPP)			Y____ N____ Not sure____
Agricultural Management Assistance (AMA)			Y____ N____ Not sure____
Conservation Technical Assistance (CTA)			Y____ N____ Not sure____
Conservation Security Program (CSP)			Y____ N____ Not sure____
Current Use Program			Y____ N____ Not sure____
I participate in programs, but can't remember which ones			Y____ N____ Not sure____
Other (please describe)			Y____ N____ Not sure____

10. If you have enrolled and participated in the programs listed in question 9, please rank your reasons for enrolling and participating from 1 to 6, with 1 being your top reason. Use each number only once.

Financial compensation		Help with farm management issues	
Conservation/environmental health		Benefiting your community and landscape	
Improve agricultural production and profitability		Other (please identify)	

11. Do you have a conservation easement on your property (check one)?

No	
Yes	
Not sure	

12. If you answered "yes" to question 11, through which organization?

____

Section 4: Please tell us about how weather and climate affect you

13. A heavy rain event will _______. (Check one statement below to complete sentence)

Have a strongly net positive impact on my farm	
Have a positive net impact on my farm	
Have no net impact on my farm	
Have a negative net impact on my farm	
Have a strongly negative net impact on my farm	
Not sure	

14. Increasing extreme temperature events will ________. (Check one statement below to complete sentence)

Have a strongly net positive impact on my farm	
Have a positive net impact on my farm	
Have no net impact on my farm	
Have a negative net impact on my farm	
Have a strongly negative net impact on my farm	
Not sure	

15. A drought event will ________. (Check one statement below to complete sentence)

Have a strongly net positive impact on my farm	
Have a positive net impact on my farm	
Have no net impact on my farm	
Have a negative net impact on my farm	
Have a strongly negative net impact on my farm	
Not sure	

16. In your opinion, is the climate changing? (Check one)

No (skip to question 18)	
Yes	
Not sure	

17. If you believe the climate is changing, do you believe this will affect your farm in a negative way? (Check one)

No	
Yes	
Not sure	

Section 5: Please tell us about your current and future use of Soil and Nutrient Management Plans

18. This question asks if you make crop and soil management decisions based on visual assessment and/or testing of soil conditions. To what extent do the following soil indicators inform your crop and soil management decisions on the farm?

0: not monitored or used at all
1: monitored, but does not influence decision-making
2: monitored, but infrequently used to inform decision-making
3: monitored, and informs decision-making, but also depends on other factors
4: monitored, and is the main factor for certain farm management decisions.
Please circle only one

How much do you use the following to make decisions?	**Circle one number per line.**
Crop yield	0 – 1 – 2 – 3 – 4
Color and vigor of plants, quality of crop	0 – 1 – 2 – 3 – 4
Soil organic matter level	0 – 1 – 2 – 3 – 4
Nutrient content: NPK - Nitrogen, Phosphorus, Potassium, minor elements	0 – 1 – 2 – 3 – 4
"Look and feel" of soil, soil tilth, aggregate stability	0 – 1 – 2 – 3 – 4
Infiltration, runoff, ponding, poor drainage	0 – 1 – 2 – 3 – 4
Topsoil depth	0 – 1 – 2 – 3 – 4
Signs of erosion (gullies, rills, dust)	0 – 1 – 2 – 3 – 4
Compaction (surface and/or subsurface hardness)	0 – 1 – 2 – 3 – 4
Soil moisture and related plant stress, available water capacity	0 – 1 – 2 – 3 – 4
Soil pH (acidity, liming requirement)	0 – 1 – 2 – 3 – 4
Signs of life: earthworms, microbial activity, etc.	0 – 1 – 2 – 3 – 4
Disease pressure and pests in plant and soil	0 – 1 – 2 – 3 – 4
Field history (nitrogen credits from previous cropping or cover cropping, residual herbicide carryover, etc)	0 – 1 – 2 – 3 – 4

19. To what extent do the following types of soil tests and the accompanying agronomic recommendations inform your farm management decisions?

0: soil test is not used at all

1: soil test is used, but does not influence decision-making

2: soil test is used, but infrequently informs decision-making

3: soil test is used, and informs decision-making, but also depends on other factors

4: soil test is used, and is the main factor for certain farm management decisions.

Please circle only one

How much do you use the following types of soil tests to make decisions?	Circle one number per line
Composite Soil health test with biological, physical and chemical indicators (e.g., Cornell Soil Health Test)	0 – 1 – 2 – 3 – 4
Chemical Soil Test (e.g., University of Vermont, University of Maine)	0 – 1 – 2 – 3 – 4
Home soil test (handheld meter, pH strips, etc)	0 – 1 – 2 – 3 – 4
Other ________________________	0 – 1 – 2 – 3 – 4

20. In the past three years, have you written or had assistance to write a comprehensive nutrient management plan? (Please check all that apply)

No (skip to question 22)	
Yes, a trained professional assisted in completing a plan	
Yes, our farm staff or owners have completed training and a plan	
Yes, the plan was approved by a State or Federal Agency	
Yes, a formal plan is in the process of being developed	
Yes, partial nutrient management planning has been done, but does not address or measure all of the components of a comprehensive nutrient management plan	
Not sure	

21. Please check all reasons why you have chosen to develop a nutrient management plan.

Regulatory Compliance	
Eligibility for Cost-Shares and Incentive Programs	
Reduce nutrient outflows to environment	
Improve agronomic production	
Increase farm efficiency	

22. Please circle the extent to which you adopted each of the following Nutrient Management Practices in the past 3 years:

Use the following numbers in the extent of adoption column:
0 = no adoption
1 = adopted at one quarter of full capacity
2 = adopted at half of full capacity
3 = adopted at three quarters of full capacity
4 = adopted at full capacity
N/A = practice not included in nutrient management plan or not applicable in my case

PRACTICE	**EXTENT OF ADOPTION (0-4)**
Planned crop rotations	0 1 2 3 4 N/A
Soil test at least every 3 years	0 1 2 3 4 N/A
Strip Cropping	0 1 2 3 4 N/A
N, P and K applications at rates recommended by soil tests	0 1 2 3 4 N/A
Buffers at field edges	0 1 2 3 4 N/A
Cover cropping	0 1 2 3 4 N/A
Reduced tillage (strip, zone, and no)	0 1 2 3 4 N/A
Applying manure at recommended rates and times	0 1 2 3 4 N/A
Applying fertilizer at recommended rates	0 1 2 3 4 N/A
Incorporating manure and fertilizer as quickly as possible after application	0 1 2 3 4 N/A
Manure spreading setbacks (from water bodies and private/public wells)	0 1 2 3 4 N/A

23. How do you feel about the adoption of the following nutrient management practices for your farming operation in the next one to three years? Please circle each practice on a scale from "very good" (1) to "very bad" (7):

Planned crop rotations	Very Good 1	2	3	Neutral 4	5	Very Bad 6	7	N/A
Soil test at least once every 3 years	1	2	3	4	5	6	7	N/A
Strip cropping	1	2	3	4	5	6	7	N/A
N, P and K application at rates recommended by soil tests	1	2	3	4	5	6	7	N/A
Buffers at edge of field	1	2	3	4	5	6	7	N/A
Cover cropping	1	2	3	4	5	6	7	N/A
Reduced tillage	1	2	3	4	5	6	7	N/A
Applying manure at recommended rates and times	1	2	3	4	5	6	7	N/A
Applying fertilizer at recommended rates	1	2	3	4	5	6	7	N/A
Incorporating manure and fertilizer as quickly as possible after application	1	2	3	4	5	6	7	N/A
Manure spreading setbacks from water bodies and wells	1	2	3	4	5	6	7	N/A

24. The next question is designed to help us understand who (friends and/or family, neighbors, or other farmers) may most strongly influence your decision to adopt conservation practices.

Under each conservation practice, please tell us how strongly you agree or disagree that friends and/or family, neighbors, or other farmers think you should adopt that practice, if applicable.

If no one influences your decisions, you can choose "not applicable" (N/A).

Planned crop rotations								
	Strongly agree			Neutral		Strongly disagree		
Your friends and/or family think you should adopt	1	2	3	4	5	6	7	N/A
Your neighbors think you should adopt	1	2	3	4	5	6	7	N/A
Other farmers think you should adopt	1	2	3	4	5	6	7	N/A

Soil tests at least once every 3 years								
	Strongly agree			Neutral		Strongly disagree		
Your friends and/or family think you should adopt	1	2	3	4	5	6	7	N/A
Your neighbors think you should adopt	1	2	3	4	5	6	7	N/A
Other farmers think you should adopt	1	2	3	4	5	6	7	N/A

Strip Cropping		
Your friends and/or family think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A
Your neighbors think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A
Other farmers think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A

N, P and K application at rates recommended by soil tests		
Your friends and/or family think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A
Your neighbors think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A
Other farmers think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A

Buffers at the edge of fields		
Your friends and/or family think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A
Your neighbors think you should adopt	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A
	Strongly agree / Neutral / Strongly disagree 1 2 3 4 5 6 7	N/A

Cover cropping								
	Strongly agree			Neutral		Strongly disagree		
Your friends and/or family think you should adopt	1	2	3	4	5	6	7	N/A
Your neighbors think you should adopt	1	2	3	4	5	6	7	N/A
Other farmers think you should adopt	1	2	3	4	5	6	7	N/A

Reduced Tillage								
	Strongly agree			Neutral		Strongly disagree		
Your friends and/or family think you should adopt	1	2	3	4	5	6	7	N/A
Your neighbors think you should adopt	1	2	3	4	5	6	7	N/A
Other farmers think you should adopt	1	2	3	4	5	6	7	N/A

Applying manure at the recommended rates and times								
	Strongly agree			Neutral		Strongly disagree		
Your friends and/or family think you should adopt	1	2	3	4	5	6	7	N/A
Your neighbors think you should adopt	1	2	3	4	5	6	7	N/A
Other farmers think you should adopt	1	2	3	4	5	6	7	N/A

Applying fertilizer at the recommended rates		
Your friends and/or family think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A
Your neighbors think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A
Other farmers think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A

Incorporating manure and fertilizer as quickly as possible after application		
Your friends and/or family think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A
Your neighbors think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A
Other farmers think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A

Manure spreading setbacks from water bodies and wells		
Your friends and/or family think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A
Your neighbors think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A
Other farmers think you should adopt	Strongly agree Neutral Strongly disagree 1 2 3 4 5 6 7	N/A

25. Are you confident that you can adopt/continue implementing the following Nutrient Management Practices? Please circle each practice on a scale from highly confident (1) to no confidence (7).

Planned crop rotations	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Soil test at least once every 3 years	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Strip cropping	Highly confident No confidence 1 2 3 4 5 6 7	N/A
N, P and K application at rates recommended by soil tests	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Buffers at edge of field	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Cover cropping	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Reduced tillage	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Applying manure at the recommended rates and times	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Applying fertilizer at recommended rates	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Incorporating manure and fertilizer as quickly as possible after application	Highly confident No confidence 1 2 3 4 5 6 7	N/A
Manure spreading setbacks from water bodies and wells	Highly confident No confidence 1 2 3 4 5 6 7	N/A

26. If you do not already use the following Nutrient Management Practices, do you intend to adopt them in the next three years? Please circle for each practice on a scale from highly likely (1) to highly unlikely (7).

Practice	**I already use this practice (y/n)**	**My intention to adopt this practice is**	
Planned crop rotations		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Soil test at least once every 3 years		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Strip cropping		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
N, P and K application at rates recommended by soil tests		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Buffers at edge of field		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Cover cropping		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Reduced tillage		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Applying manure at the recommended rates and times		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Applying fertilizer at recommended rates		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Incorporating manure and fertilizer as quickly as possible after application		Highly likely Unlikely 1 2 3 4 5 6 7	N/A
Manure spreading setbacks from water bodies and wells		Highly likely Unlikely 1 2 3 4 5 6 7	N/A

Section 6: Please tell us about yourself – your information will be kept confidential

27. In addition to your farm work, do you work off-farm at any point during the year? Please check one.

No	
Yes	
Not sure	

28. What percent of your household income is generated from the farm?

___________%

29. What was the **gross** income from your farm in 2015? Please check one.

$0-$9,999		$100,000 - $124,999	
$10,000 - $24,999		$125,000 - $149,999	
$25,000 - $49,999		$150,000 - $174,999	
$50,000 - $74,999		$175,000 - $199,999	
$75,000 - $99,999		$200,000+	

30. What was the **net** income for your farm in 2015? Please check one.

Less than $0 (net loss)			
$0 - $9,999		$100,000 - $124,999	
$10,000 - $24,999		$125,000 - $149,999	
$25,000 - $49,999		$150,000 - $174,999	
$50,000 - $74,999		$175,000 - $199,999	
$75,000 - $99,999		$200,000+	

31. In what year were you born? Please check one.

1910-1919		1960-1969	
1920-1929		1970-1979	
1930-1939		1980-1989	
1940-1949		1990-1999	
1950-1959			

32. Highest level of education achieved? Please check one.

Some high school		Associate's Degree	
High school degree/GED		Bachelor's Degree	
Some college		Graduate Degree	

Thank you for finishing the survey!

Glossary Definitions

Adaptation: Planning for the changes that are expected to occur as a result of climate change. (EPA)

Agroforestry: Agroforestry intentionally combines agriculture and forestry to create integrated and sustainable land-use systems. Agroforestry takes advantage of the interactive benefits from combining trees and shrubs with crops and/or livestock. (USDA National Agroforestry Center)

Animal Feed Management: Feeding a balanced diet, avoiding overfeeding, and providing abundant supplies of cool, clean, and pure water will help to optimize feed and nutrient use on an animal farm. (UVM Extension, eXtension)

Bank and Channel Erosion: Stream stability is an active process, and while streambank erosion is a natural part of this process, it is often accelerated by altering the stream system. Streambank erosion is that part of the channel erosion in which material is eroded from the streambank and deposited at the base of the slope or in the channel. Streambank erosion is usually associated with erosion of the streambed. It occurs along perennial, intermittent, and ephemeral streams. (NRCS)

Composite Soil Health Test: The concept of soil health deals with integrating the physical, biological and chemical components of the soil. Physical components include but are not limited to texture, bulk density, and Macro-porosity. Biological components include but are not limited to organic matter content, microbial respiration rate, and soil proteins. Chemical components include but are not limited to P, N, K, and PH. (http://www.css.cornell.edu/extension/soil-health/manual.pdf)

Conservation buffers: Strips of land maintained in permanent vegetation. These buffers can be used in a systems approach to manage soil, water, nutrients, and pesticides for sustainable agricultural production, while minimizing environmental impact. (NRCS)

Conservation tillage (Reduced tillage): A number of strategies and techniques for establishing crops in the previous crop's residues, which are purposely left on the soil surface. The principal benefits of conservation tillage are improved water conservation and the reduction of soil erosion. Additional potential benefits include reduced fuel consumption, planting and harvesting flexibility, reduced labor requirements, and improved soil tilth. Two of the most common conservation tillage systems are zone tillage and no-till. (ATTRA)

Cover crops: Crops, including grasses, legumes, and forbs, used to provide vegetative cover for natural resource protection and improvement. (USDA)

Creek: In North America, Australia and New Zealand, a small to medium-sized natural stream. Sometimes navigable by motor craft and may be intermittent. (Wikipedia)

Deep zone tillage: Deep zone tillage uses a 5-inch-wide tilled strip to simultaneously break up plow pans, warm the soil and prepare a seedbed. A deep shank or subsoiler (zone-builder) breaks up the plow-pan while fluted coulters cut and prepare a strip in the killed residue/cover crop, and rolling baskets help break up soil clods to prepare the narrow seedbed. (University of Connecticut)

Drainage tile: A type of subsurface drainage used in areas with moist soils or the experience standing water. The purpose of subsurface drainage is to lower the water table in the soil. The water table is the level at which the soil is entirely saturated with water. The excess water must be removed to a level below the ground surface where it will not interfere with plant root growth and development. (Iowa State University)

Crop rotation: Growing crops in a planned sequence on the same field. (NRCS)

Green Manure: The term "green manure" refers to cover crops that are tilled into the soil. Green manures are mainly grown to increase soil organic matter (OM). (NRCS)

Gully/Concentrated Flow Erosion: Ephemeral and classic gully are forms of erosion created by the concentrated flow of water. They are easily identified through visual observation. An ephemeral cropland gully is larger than a rill and smaller than a classic gully. They usually result from the junction of rills that form a branching or tree-like pattern of channels. Ephemeral gullies usually appear on cultivated fields during the planting or growing season, but are temporarily removed by cultivation. (NRCS)

Hoop Houses/High Tunnels: A seasonal tunnel system is a polyethylene (plastic) covered structure that is used to cover crops to extend the growing season. They are also known as high tunnels, hoop houses, or cold tunnels. They are used to extend the growing season for crops by approximately two to three weeks on each end of the season by increasing the temperature surrounding the crop and minimizing the heat loss during the night. (NRCS)

Keyline plowing: Keyline plowing can help alleviate compaction and has been reported to help improve soil quality and build organic matter. The thin, cast shanks (~3/4") and coulter wheels of the Yeomans' Keyline subsoil plow aerate subsoil while causing minimal disruption to the pasture surface. (University of Vermont)

Mitigation: Mitigation refers to technological change and substitution that reduce energy resource inputs and emissions per unit of output. Specific to climate change, mitigation encompasses implementing policies and practices to reduce greenhouse gas emissions and to enhance sinks. (IPCC, 2001).

No till: **No-till cropping systems** are based on the concept of keeping the soil covered at all times. They include the use of crop rotations, cover cropping, and planting into a seed slot created by coulters. (NRCS)

Nutrient management plan: Established plan for managing the amount (rate), source, placement (method of application), and timing of plant nutrients and soil amendments. Benefits include nutrient conservation and improved air, water, and soil quality. This practice applies to all lands where plant nutrients and soil amendments are applied. This standard does not apply to one-time nutrient applications to establish perennial crops. (USDA)

Rotational Grazing: Exposing animals to limited grazing areas for set periods of time, then providing adequate periods of rest for the grass. The system requires careful management to ensure that animals do not trample or eat grass so close to the ground that its regrowth is hampered. It is sometimes called "prescribed" if grazing systems are set up in advance, paddocks are numbered, and movement of the animals progresses in a prescribed order. (UVM Center for Sustainable Agriculture)

Sheet, Rill and Wind Erosion: Wind or water erosion is the physical wearing of the earth's surface. Erosion is not always readily visible even when soil loss exceeds unsustainable levels. Symptoms of soil erosion by water may be identified by small rills and channels on the soil surface, soil deposited at the base of slopes, sediment in streams, lakes and reservoirs, and pedestals of soil supporting pebbles and plant material. Water erosion is most obvious on steep, convex landscape positions. Symptoms of wind erosion may be identified by dust clouds, soil accumulation along fence lines or snowbanks and a drifted appearance of the soil surface. (NRCS)

Soil tilth: Physical condition of soil, especially in relation to its suitability for planting or growing a crop. Factors that determine tilth include the formation and stability of aggregated soil particles, moisture content, degree of aeration, rate of water infiltration, and drainage. (http://www.britannica.com/science/tilth)

Strip cropping: Growing planned rotations of row crops, forages, small grains, or fallow in a systematic arrangement of equal width strips across a field. (NRCS)

Stormwater runoff management: Stormwater runoff is generated when precipitation from rain and snowmelt events flows over land or impervious surfaces and does not percolate into the ground. As the runoff flows over the land or impervious surfaces (paved streets, parking lots, and building rooftops), it accumulates debris, chemicals, sediment or other pollutants that could adversely affect water quality if the runoff is discharged untreated. The primary method to control stormwater discharges is the use of best management practices (BMPs). (EPA)

Wetlands conservation: Protecting wetlands, wildlife habitat, soil, water, and related natural resources in an environmentally beneficial and cost effective manner. (USDA)

Vernal pools: They also called vernal ponds or ephemeral pools, are temporary pools of water that provide habitat for distinctive plants and animals. (Wikipedia)

Appendix C Supplementary Materials for Chapter 4

Residential Survey

20. Please indicate whether or not each of the following is a barrier to adopting *infiltration trenches*.

	Yes	No
Not enough space	○	○
Costs too much	○	○
No interest	○	○
Don't believe it works	○	○
Too much upkeep	○	○
No need	○	○
Against property rules	○	○
Doesn't look good	○	○
Not suitable on my property	○	○
Not enough information to decide	○	○

21. Please indicate whether or not each of the following is a barrier to adopting *tree box filters*.

	Yes	No
Not enough space	○	○
Costs too much	○	○
No interest	○	○
Don't believe it works	○	○
Too much upkeep	○	○
No need	○	○
Against property rules	○	○
Doesn't look good	○	○
Not suitable on my property	○	○
Not enough information to decide	○	○

22. Please indicate whether or not you would be willing to adopt the following Green Stormwater Infrastructure Practices for the associated prices.

Would you be willing to pay...	Yes	No
$250 to purchase and install a rain barrel at your residence?	○	○
$310 for a rain garden at your residence?	○	○
$600 for permeable pavers at your residence?	○	○
$560 for a rain barrel and rain garden at your residence?	○	○
$850 for a rain barrel and permeable pavers at your residence?	○	○

22. (cont.) Would you be willing to pay...	Yes	No
$910 for a rain garden and permeable pavers at your residence?	○	○
$1160 for a rain barrel, rain garden, and permeable pavers at your residence?	○	○
$90 annually for your town to make green stormwater infrastructure improvements?	○	○

23. Which of the following factors would likely influence your decision to adopt green stormwater infrastructure practices on your property? Please rank your top 3 by placing a "1" next to the item you consider most likely to influence your decision, a "2" next to the item you consider second most likely to influence your decision, etc.

___ Wanting to fix problems related to flooding
___ Desire to be eco-friendly
___ Opinions of friends and family
___ Incentives or subsidies for adopting
___ Tax breaks for adopting
___ Taxes imposed for not adopting
___ Regulations
___ Aesthetics
___ Other ______________________

Lastly, we have a few questions about you. These are purely for the purpose of classification, and no identifying information will be released.

24. What is your gender?

○ Male
○ Female

25. What year were you born? 19___ ___

26. What is the highest level of education you have completed?

○ Less than 9th grade
○ 9th to 12th grade, no diploma
○ High school graduate (including GED)
○ Some college, no degree
○ Associate's degree
○ Bachelor's degree
○ Graduate or professional degree

27. What is your household income?

○ Less than $10,000
○ $10,000 to $14,999
○ $15,000 to $24,999
○ $25,000 to $34,999
○ $35,000 to $49,999
○ $50,000 to $74,999
○ $75,000 to $99,999
○ $100,000 to $149,999
○ $150,000 to $199,999
○ $200,000 or more

PLEASE FEEL FREE TO ATTACH ANY ADDITIONAL COMMENTS. THANK YOU FOR YOU PARTICIPATION!

Green Infrastructure Survey for Vermont Residential Properties

Survey administered by the Castleton Polling Institute
Phone: (802) 770-7042 – Email: polling@Castleton.edu

Are you the primary decision maker for your current residence? If not, please ask the decision maker to complete this survey.

1. Where does the majority of your stormwater runoff go immediately after it leaves your property? (Please check all that apply.)

☐ It doesn't leave the property; it is retained and soaks into the ground on site.
☐ It enters a stormwater treatment system.
☐ It enters a storm sewer pipe.
☐ It enters a combined sewer pipe.
☐ It flows down the road.
☐ It enters a nearby stream or ditch.
☐ I don't know.
☐ Other ______________

2. The stormwater collected from your neighborhood eventually goes to:

○ Lake Champlain
○ Connecticut River
○ Lake Memphremagog
○ Groundwater
○ I don't know
○ Other ______________

3. Do you think stormwater runoff is a problem in your neighborhood?

○ Yes
○ No
○ I don't know

4. Do you think flooding is a problem in your neighborhood?

○ Yes
○ No
○ I don't know

5. In the past 3 years, which, if any of the following problems have you experienced at your primary residence? (Please check all that apply.)

☐ Flooding on property
☐ Basement flooding
☐ Runoff, erosion, and washouts of driveway or road to your house
☐ Runoff, erosion, and washouts of lawns or gardens

6. If stormwater is a problem in your neighborhood, who do you think has the responsibility for fixing the problem? (Please select only one.)

○ Federal agencies
○ State of VT
○ The town
○ Builder or developer
○ Residents
○ Don't know
○ Stormwater is not a problem in my neighborhood

7. What type of primary residence do you have?

○ Single family
○ Multi-family
○ Apartment
○ Condominium

8. Do you own or rent your primary residence?

○ Own
○ Rent

9. What is the lot size of your primary residence? If it's multiple unit, please estimate size for the entire property.

○ No Land
○ Less than 1/10 of an acre
○ 1/10 to less than ¼ acre
○ 1/4 to less than ½ acre
○ ½ acre to 1 acre
○ Greater than 1 acre
○ I don't know

10. Around what proportion of your lot area is built (e.g. covered in buildings, structures, driveway, or parking surfaces)?

○ Less than 10%
○ 10-24%
○ 25-49%
○ 50-74%
○ 75-90%
○ Greater than 90%

11. Do you make the decisions about your landscape and property management?

- ○ Yes, decisions are made in my household about landscaping
- ○ No, I rent and the property manager or owner makes these decisions
- ○ No, the decisions for the landscaping are taken care of by a property manager and/or neighborhood decision-making body (e.g. homeowner association, etc.)
- ○ It depends, individual landscape decisions are discussed with our landlord and/or our neighborhood's decision-making bodies

In this next section, we'd like to know about your usage of compost and fertilizer on your property.

12. What is your usage of compost on your property?

- ○ Have not used compost
- ○ Have used compost in isolated areas of land
- ○ Have used compost on most of land
- ○ I don't know
- ○ Not applicable because no land area

13. What is your usage of fertilizer on your property?

- ○ Have not used fertilizer
- ○ Have used fertilizer on isolated areas of land
- ○ Have used fertilizer on most of land
- ○ I don't know
- ○ Not applicable because no land area

In this next section, we will be asking you about specific green infrastructure practices, and whether or not you have implemented them on your property. If you are uncertain what any of the terms mean, please refer to the definitions we have provided below.

"*Green infrastructure*" includes many different practices that homeowners and residents can use to slow stormwater runoff and increase treatment of pollutants including sediment, nutrients, bacteria, heavy metals, etc., helping make downstream water bodies cleaner and healthier.

"Impervious surfaces" at the residential scale include rooftops, driveways, or walkways that do not allow water to soak into the ground and be filtered, contributing to stormwater runoff (water flowing off site).

"Rain barrels" are small cisterns, typically 50-75 gallons, that collect rain from roofs and gutter systems that can be stored and/or reused for irrigation.

"Rain gardens" (bio retention) are sunken gardens that are designed to receive, store, and clean stormwater from roofs and paved areas during rain events. Water does not pond in rain gardens for more than 12 to 24 hours, and they can host a variety of different types of vegetation.

"Permeable pavement/pavers" can replace impervious surfaces such as sidewalks or driveways to allow for infiltration on site and keep runoff water from flowing quickly off the land.

"Infiltration trenches" are rock-filled trenches that receive stormwater runoff from roofs and paved areas. Runoff is stored in the empty space between the stones and infiltrates through the bottom of the trench and into the soil.

"Tree box filters" are small runoff storage systems, usually in a buried planter box with one or more large trees. They can replace traditional stormwater catch basins and treat small drainage areas.

"Green roofs" use thin layers of vegetation, planted in beds or trays on rooftops, to temporarily slow the flow of runoff from roofs, insulate buildings, and increase evaporation through plants.

"Constructed wetlands" mimic the look and function of natural wetlands to effectively remove sediment and pollutants from paved surfaces, and reduce the peak flows of stormwater. They may have areas of open water or store water sub-surface.

14. Which, if any, of the following practices are currently implemented at your primary residence (adopted and maintained)? (Please check all that apply.)

- ☐ Actively divert roof runoff to a rain barrel or to lawn or garden instead of to street/sewer
- ☐ Rain garden (bio retention)
- ☐ Permeable pavement/pavers
- ☐ Gravel or sand infiltration trenches
- ☐ Tree box filters
- ☐ Green roofs
- ☐ Constructed wetlands
- ☐ Other ________________

15. Regardless of what is being done now, please identify any of the following practices that have been implemented in the past but may no longer be maintained or functioning effectively. (Please check all that apply.)

- ☐ Actively divert roof runoff to a rain barrel or to lawn or garden instead of to street/sewer
- ☐ Rain garden (bio retention)
- ☐ Permeable pavement/pavers
- ☐ Gravel or sand infiltration trenches
- ☐ Tree box filters
- ☐ Green roofs
- ☐ Constructed wetlands
- ☐ Other ________________

16. Please indicate how likely you are to adopt each of the following practices in the next three years.

	Unlikely 0	1	2	3	4	Highly Likely 5	Currently Used
Actively divert roof runoff to a rain barrel or to lawn or garden instead of to street/sewer	○	○	○	○	○	○	○
Rain garden (bio retention)	○	○	○	○	○	○	○
Permeable pavement/pavers	○	○	○	○	○	○	○
Infiltration trenches	○	○	○	○	○	○	○
Tree box filters	○	○	○	○	○	○	○
Green roofs	○	○	○	○	○	○	○
Constructed wetlands	○	○	○	○	○	○	○

17. Please indicate whether or not each of the following is a barrier to adopting *active diversion of roof runoff to a rain barrel or to a lawn or garden instead of to the street/sewer.*

	Yes	No
Not enough space	○	○
Costs too much	○	○
No interest	○	○
Don't believe it works	○	○
Too much upkeep	○	○
No need	○	○
Against property rules	○	○
Doesn't look good	○	○
Not suitable on my property	○	○
Not enough information to decide	○	○

18. Please indicate whether or not each of the following is a barrier to adopting *a rain garden (bio retention).*

	Yes	No
Not enough space	○	○
Costs too much	○	○
No interest	○	○
Don't believe it works	○	○
Too much upkeep	○	○
No need	○	○
Against property rules	○	○
Doesn't look good	○	○
Not suitable on my property	○	○
Not enough information to decide	○	○

19. Please indicate whether or not each of the following is a barrier to adopting *permeable pavement/pavers.*

	Yes	No
Not enough space	○	○
Costs too much	○	○
No interest	○	○
Don't believe it works	○	○
Too much upkeep	○	○
No need	○	○
Against property rules	○	○
Doesn't look good	○	○
Not suitable on my property	○	○
Not enough information to decide	○	○

Survey Methods

Table 1. Mail Dates by Contact Piece by Survey Version

	Pilot	Version 1	Version 2
Prenotification	6/2/2015	7/2/2015	7/13/2015
Survey	6/8/2015	7/8/2015	7/17/2015
Postcard	7/15/2015	7/15/2015	7/24/2015

Table 2. Post-Stratification Regions

	Counties
Region 1	Addison, Chittenden, Washington
Region 2	Grand Isle, Franklin, Lamoille, Orleans, Essex, Caledonia, Orange
Region 3	Rutland, Windsor, Windham, Bennington

The estimated sampling error (without adjusting for a design effect) for the total number of completed interviews (N=577), at a 95% confidence level with an assumed 50/50 response is (+/-) 4.08. This margin of error is based on the estimated total number of households (N=257,004) in Vermont. Any analysis utilizing a sub-group (e.g., comparing across counties) will be less precise and have a greater margin of error.

Classifications for survey data

1. Urban Type: For the 2010 Census, an urban area will comprise a densely settled core of census tracts and/or census blocks that meet minimum population density requirements, along with adjacent territory containing non-residential urban land uses as well as territory with low population density included to link outlying densely settled territory with the densely settled core. To qualify as an urban area, the territory identified according to criteria must encompass at least 2,500 people, at least 1,500 of which reside outside institutional group quarters. The Census Bureau identifies two types of urban areas:

   - Urbanized Areas (UAs) of 50,000 or more people;
   - Urban Clusters (UCs) of at least 2,500 and less than 50,000 people.

   "Rural" encompasses all population, housing, and territory not included within an urban area.https://www.census.gov/geo/reference/ua/urban-rural-2010.html

   Layer: tl_2016_us_uac_10 (downloaded Tiger Census data, clipped to Vermont)

2. MS4 in Vermont

In the state of Vermont, all of the issued MS4 permits fall under the Phase II general permit (Vermont Department of Environmental Conservation, n.d.). The permitting schedule is about every ten years; so the first permits were established in 2004 and were renewed with additional muncipalities added in 2012 (Vermont Department of Environmental Conservation, n.d.). Burlington, Town of Colchester, Town of Essex, Village of Essex Junction, Town of Milton, Town of Shelburne, City of South Burlington, Town of Willison, City of Winooski, as well as Burlington International Airport, and the Vermont Agency of Transportation have had Phase II permits since 2004 (Vermont Department of Environmental Conservation, n.d.). In 2012, the City of St Albans, the Town of St Albans, and the town of Rutland were added (Vermont Department of Environmental Conservation, n.d.). With the exception of the Vermont Department of Transporation that covers the entire state, all of the other issued MS4 permits are in the the Lake Champlain Basin. In addition, the Town of Milton is the only permitted small MS4 in Vermont that does not discharge directly to stormwater impaired waters listed on the 303d List (Vermont Department of Environmental Conservation, 2016, n.d.).

3. Development related stormwater impairment

Examples of pollutant sources that were included as development related stormwater impairment include: WWTF overflows at pump stations, stormwater runoff, land development, construction related erosion, stormwater elevated temperatures, combined sewer overflows, *E. coli* stormwater runoff, increased peak stormwater flows, erosion from stormwater discharges, corroding road culverts. Pollution attributed to agricultural or industrial sources was excluded (U.S. Geological Survey et al., 2010; VT DEC, 2016).