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Multidisciplinary Thinking to Increase Sustainability in Engineering:

A Case Study in Sanitation

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Multidisciplinary Thinking to Increase Sustainability in Engineering:

A Case Study in Sanitation

by

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Dedication

This dissertation is dedicated to the late bloomers, the do-it-all-ers, the engineers-and. It might not be possible to do it all, but it is possible to do an awful lot. Not all those who wander are lost;[1] some of us just take longer to get there.

[1] J.R.R. Tolkien

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Multidisciplinary Thinking to Increase Sustainability in Engineering: A Case Study in Sanitation

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This dissertation uses a case study in sanitation that illustrates the need for interdisciplinary analysis of sustainable solutions to engineering problems. This case study also suggests that one nontechnical factor that might be critical for increasing sustainability is consumer willingness to use the technology, which, along with factors such as cost, will drive technology adoption rates. By developing the ability and willingness to recognize needs for this type of interdisciplinary work and by collaborating with experts in other fields, engineers can more successfully create sustainable solutions to the problems they tackle.

The work of this dissertation is in three stages. The first comprises a life cycle cost and cost-effectiveness analysis for a suite of household sanitation technologies. Results of this stage suggest that decentralized technologies are lower cost and more cost-effective for nitrogen management than conventional centralized wastewater treatment in the given case study location; composting and urine-diversion toilets proved the best performers on these metrics. The second stage of research expands the analysis to examine adoption of decentralized sanitation technologies as a two-party decision, with

the individual discount rate used as a proxy for factors influencing homeowners' adoption decisions. Results in two case study locations emphasize the dependence of analysis on case-specific details; in one case, monetary incentives are expected to be successful at bringing municipal and individual decision-makers into agreement to adopt decentralized sanitation systems under many cost scenarios, while monetary incentives are not expected to succeed at bringing about agreement between parties in the other case. The third stage of research uses a survey to examine non-monetary factors influencing homeowners' adoption decisions surrounding composting and urine-diversion toilets. Results suggest that educational efforts are likely to be important in influencing adoption decisions, although not all homeowners will be swayed by additional information.

Together, the three stages of this research illustrate how understanding of technologies as potential solutions to problems of sustainability changes as the analysis expands to incorporate methods from more disciplines. While true assessment of "sustainability" is difficult at best, movement toward increasingly sustainable technologies can be facilitated by broader analyses that lead to more thorough understanding.

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Chapter 1: Introduction

Sustainable sanitation might be considered the purview of environmental engineers, as they typically design sanitation technologies. However, because many other people interact with any sanitation system specifically and with sustainable technologies in general, true understanding of such technologies and their potential for solving problems cannot be relegated entirely to the world of engineering. Engineers are skilled in creating technical solutions to technical problems, but sustainability problems often have facets beyond the technical, such as economic and social, both of which are encompassed in the U.S. EPA's definition of sustainability.[1] Attempting to solve a broadly defined problem with a purely technical solution will leave some parts of the problem unsolved. While interdisciplinary collaborations can be challenging, they are necessary to incorporate the many facets of such problems and their solutions. Such collaborations can apply expertise from many fields, including engineering, to simultaneously address the multiple dimensions of a problem and thus the multiple dimensions of sustainability.

Sustainability is often thought to imply environmental protection, but its most widely accepted definitions encompass much more. The oft-cited Report of the World Commission on Environment and Development,[2] commonly referred to as the Brundtland Commission Report, envisions sustainable development as including economic, social, and political aspects, as well as environmental. If we accept the Commission's definition of sustainable development as development that "ensure[s] that it meets the needs of the present without compromising the ability of future generations to meet their own needs," or the EPA's definition that "sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations," we see immediately that any "sustainable" technology, process, strategy, or other solution is inherently multifaceted. Engineers are skilled at addressing certain aspects of sustainability, but additional expertise is needed to address other aspects. It might be unreasonable to incorporate all possible dimensions of sustainability into every solution to every problem and it might be unnecessary to do so. However, expanding on the great technical innovations generated by engineers in even a few dimensions will enhance these innovators' work and increase the sustainability of the ultimate products of the work.

This dissertation uses a case study in sanitation that illustrates the need for interdisciplinary analysis of sustainable solutions to engineering problems. This case study also suggests that one nontechnical factor that might be critical for increasing sustainability is consumer willingness to use the technology, which, along with factors such as cost, will drive technology adoption rates. By developing the ability and willingness to recognize needs for this type of interdisciplinary work and by collaborating with experts in other fields, engineers can more successfully create sustainable solutions to the problems they tackle.

This case study examines a variety of household sanitation systems for use in the U.S., where the current most common technologies meet basic sanitation goals but fall short of sustainability in a variety of ways. Systems that are currently less common in U.S. homes, such as composting and urine-diversion toilets (eco-toilets), are technically capable of reducing environmental pollution and increasing the feasibility of resource reuse. However, eco-toilets can only succeed in achieving sustainability objectives if people are willing to purchase and use them. Thus in this work we investigate the cost and cost-effectiveness of several sanitation technologies, the potential for financial incentives to offset prohibitive costs borne by individual homeowners, and people's willingness to install some of the least conventional options (eco-toilets) in their own homes. In this way, this dissertation incorporates some measures of technical capacity and financial viability but also considers several dimensions that might be critical when high adoption rates by individuals are necessary for a technology's success. Although this case study is not an exhaustive analysis of all facets of sustainable sanitation, the aspects addressed herein demonstrate how factors outside of engineering can impact the success and ultimate sustainability of technological solutions.

In this dissertation, "sustainable" sanitation is examined in three stages, beginning with conventional engineering concepts and gradually expanding to draw from other disciplines, thus augmenting the concept of "sustainability" in sanitation to include factors beyond environmental protection. Six research questions state more specifically the goals of the work undertaken in these three stages:

1. What are the total costs, nitrogen mitigation potential, and cost-effectiveness of a range of conventional and alternative municipal wastewater treatment technologies?
2. What uncertainties influence these cost, nitrogen mitigation, and cost-effectiveness outcomes and how can we improve our understanding of these technologies?
3. How do life cycle cost comparisons change when individual discount rates are incorporated?
4. How does analysis with individual discount rates help set expectations about the need for and success of adoption incentive programs?
5. Are U.S. homeowners in locations with wastewater management problems willing to install eco-toilets in their own homes?
6. Can any patterns be discerned in how willingness to install relates to relevant attitudes and perceptions or to demographic characteristics?

The first stage uses the common engineering metrics of life cycle cost and cost-effectiveness to compare a suite of household sanitation technologies that could be implemented as part of a larger nitrogen mitigation strategy in a sensitive coastal environment on Cape Cod, Massachusetts. This study estimates a household nitrogen balance, which is used in conjunction with life cycle costs to find the cost-effectiveness of each technology in terms of its nitrogen removal potential.

In the second stage, the analysis is extended to consider the individual discount rate, which reflects how individuals make purchasing decisions more accurately than the discount rates used in the first stage, which are appropriate for public works and projects funded by private businesses. This stage of the work also examines the implications of the revised cost comparison for incentives that might be offered to increase adoption rates of decentralized technologies that homeowners might be reluctant to install. To illustrate the broad applicability of the methods of the study, this implicit discount rate analysis was completed both for Falmouth, on Cape Cod, and for the service area of the Allegheny County Sanitary Authority (ALCOSAN), in Pennsylvania, where combined sewer overflows are prompting expensive infrastructure upgrades.

In the final stage, non-monetary factors that also might influence individuals' decision-making are surveyed to give a fuller picture of potential adoption rates of eco-toilets, which are the least common (in U.S. homes) of the technologies. These data help illuminate the potential for these systems to successfully provide sustainable sanitation services, since a technology can only succeed in accomplishing environmental goals if it is adopted. A questionnaire developed for this study was used to gather data on homeowners' willingness to adopt eco-toilets (composting and urine-diversion toilets) and on various attitudes and perceptions that might influence willingness to adopt, along with demographic information. Implementation of this questionnaire was centered on Harwich, Massachusetts, and expanded to other communities on Cape Cod.

Together, these three studies show how the results of a conventional engineering analysis (the first stage of research) shift as additional factors are considered: first an extension of the economic concepts already incorporated, and then a broadening to include aspects normally outside the sphere of engineering. The technical capabilities manifest in the initial analysis of the technologies become one part of a more complex picture that reflects other aspects of sustainability. Thus the changing understanding of the sustainability of various sanitation options as more factors are incorporated illustrates the need for interdisciplinary work, reaching beyond the bounds of engineering, to solve sustainability problems.

The remaining chapters of this dissertation discuss the three stages of this research. Chapter two introduces the technologies examined in the analyses and discusses interdisciplinarity and sustainability. Chapters three, four, and five detail the first (cost and cost-effectiveness), second (individual discount rate), and third (household survey) stages of the research, respectively. Chapter six provides a concluding discussion of how the research as a whole meets the goals of (1) demonstrating that drawing methods from multiple disciplines adds important understanding of the potential for so-called sustainable technologies to solve engineering problems, and (2) illustrating specific techniques that can be used to understand adoption of decentralized technologies.

References

(1) U.S. Environmental Protection Agency. Sustainability http://www.epa.gov/sustainability/basicinfo.htm (accessed Mar 22, 2015).

(2) The World Commission on Environment and Development. *Our Common Future*; Oxford University Press: New York, 1987.

Chapter 2: Background

The goals of household sanitation have evolved over time as population growth and increasing settlement density have increased the amount of human waste and decreased the options for simply moving this waste to remote locations. Simultaneously, increased scientific and engineering knowledge has further delineated the negative effects of those wastes on public health and the environment. Early goals included managing the nuisance of odors and reducing the spread of disease, goals that are still important today. Environmental goals became increasingly important in the 20th century, with an uptick in efforts after the 1972 implementation of the Clean Water Act. Sanitation systems that had focused on biological oxygen demand (BOD), suspended solids, and pathogens added objectives to reduce nutrients in effluent, followed by increasing focus on various toxins.[1] As new chemicals are introduced through ever-advancing industrial processes and as scientists and engineers learn more about the effects of these chemicals on humans and the environment, wastewater is subjected to higher levels of treatment to avoid negative outcomes. Better treatment also is sought as longstanding environmental problems, such as nutrient pollution and ensuing eutrophication, reach critical levels, in part because of the increasing population density. The capacity of natural waters to assimilate the contamination without deterioration has been exceeded in these cases. In 2000, nutrient pollution and eutrophication were called “the largest pollution problem facing the vital coastal waters of the United States,”[2] and in 2013 they were noted as “a leading cause of impairment in many freshwater and coastal marine ecosystems in the world.”[3] As much as 63% of the nitrogen entering coastal waters and contributing to this pollution problem comes from sewage.[4]

The most common systems used in the U.S. today for managing human waste are on-site septic systems and centralized wastewater treatment plants with sewer collection networks (WWTPs): approximately 81% of occupied housing units are served by public sewers, and approximately 19% are served by “septic tank, cesspool, or chemical toilet.”[5] Septic systems are more commonly found in rural regions and small towns, where low housing density increases the cost per household of installing sewer networks.[6] Centralized treatment is frequently considered the gold standard of wastewater treatment,[7] but it is becoming more widely recognized that, for many communities, centralized systems "may never be possible or desirable, for both geographical and economic reasons."[8] In the next two sections, a brief explanation of these common systems is given, followed by a description of various alternative systems. Subsequently, sustainability and interdisciplinarity are introduced. These subjects frame the remaining work of this dissertation.

CONVENTIONAL SEPTIC SYSTEMS

Septic systems consist of a septic tank and some type of soil infiltration system with a distribution mechanism to carry effluent from the tank into the soil system. Figure 2.1 shows a schematic of a septic tank. The tank provides primary treatment, allowing solids to settle and floatables to rise to the top surface; effluent is drawn from the clearer liquid between the scum layer on top and the sludge blanket on the bottom of the tank. Anaerobic digestion of the sludge produces gases that, as they rise, carry floatable material to the surface to form the scum layer; this digestion also reduces the volume of solids and allows for longer operation periods between required maintenance. A screen or filter of some kind is recommended at the tank outlet to reduce the amount of solids exiting the tank with the effluent, as these can clog the distribution and infiltration system. Effluent is distributed from the tank into the soil system either through gravity flow or pumped dosing. Once it has been distributed over the infiltrative surface, the effluent undergoes further physical, chemical, and biological treatment as it filters through the biomat that forms at the interface between the distribution surface and the underlying soil system, and then through that underlying soil. Results of this treatment vary depending on soil type, wastewater characteristics, and hydraulic loading, but in a properly functioning septic system, 90% or more of BOD and 99% of bacteria can be removed in the biomat and infiltration zone.[6] A well-functioning system can also achieve 10-20% nitrogen removal in the soil system;[6]

the remainder of the nitrogen in the effluent typically enters the groundwater in the form of nitrate, because ammonium in wastewater is almost completely nitrified, while denitrification in soil systems is limited.[6,9]

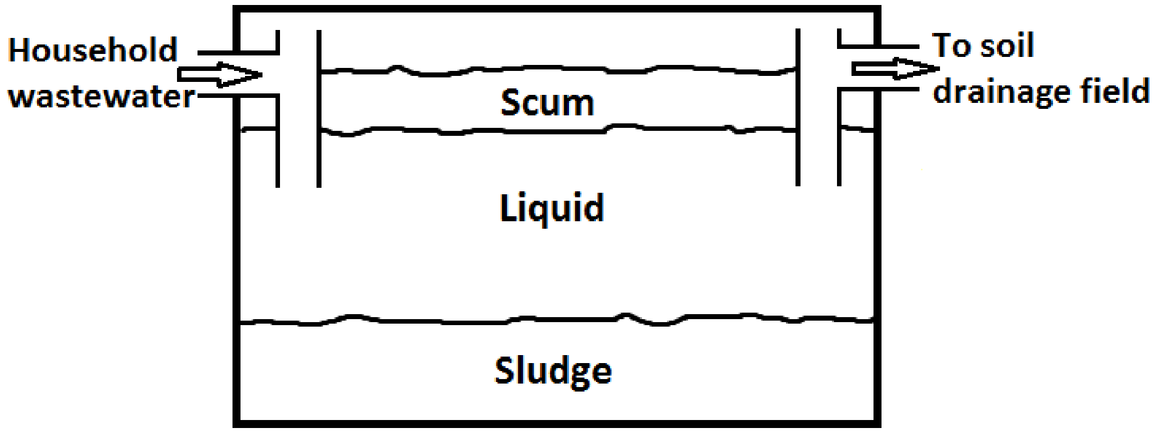

Figure 2.**Error! Use the Home tab to apply 0 to the text that you want to appear here.**.1. Septic tank schematic.

Proper design, installation, and operation and maintenance of the septic system are critical to keep the soil infiltration system functioning at a high level. For example, exceeding the hydraulic capacity of the infiltration system creates anaerobic conditions and can reduce infiltrative capacity, both of which reduce the level of treatment provided by the system. System failures are common, with approximately 10-20% of systems failing nationwide.[6] Even properly functioning systems can contribute to local water pollution if the assimilative capacity of the environment is exceeded by the total load from all installed septic systems. Nitrogen in particular can become problematic in sensitive coastal locations such as Cape Cod, because it is not well managed by conventional septic systems and nitrate moves freely through groundwater.[6,10] Sandy soils, with high conductivity compared to denser soils, exacerbate the problem.[11]

Because sludge and scum accumulate in a septic tank (they are only partially digested by anaerobic processes), they must be periodically removed for disposal. Accumulated sludge and scum reduce the volume of the tank, which reduces detention time and in various other ways threatens to reduce the treatment capacity of the system. Pumping removes the entire contents of the tank: all sludge, scum, and liquid in the tank at the time. These contents, a slurry known as septage, can be disposed of in several ways: at a wastewater treatment plant for treatment along with incoming wastewater, at a treatment plant dedicated to septage handling, by land application through spray irrigation or subsurface incorporation, or occasionally by dewatering followed by disposal in a sanitary landfill.[6]

Centralized Wastewater Treatment Plants and Sewer Collection Networks

Centralized wastewater treatment plants vary widely in design, depending on flow, contaminant loadings, and various other local conditions such as availability of funding and sensitivity of local environment, but they are all based on similar principles. Figure 2 shows a typical wastewater treatment train schematic. Preliminary treatment at the head of the plant uses physical operations to remove solids and grit that would damage plant equipment if left in the wastewater. Primary treatment uses physical sedimentation to remove 50-70% of suspended solids and 25-40% of the incoming BOD.[10] Secondary treatment is biological treatment, using organic constituents in the wastewater as substrate for microbial growth. This stage of treatment removes 65-95% of BOD depending on the specific unit process and produces additional biomass that must be removed with secondary sedimentation.[1] The most common biological unit process in wastewater treatment plants is activated sludge, in which a portion of the sludge from secondary sedimentation is recycled into the heavily aerated biological treatment reactor to provide sufficient biomass for proper treatment. All biological processes commonly used in secondary treatment are aerobic, with water and carbon dioxide generated as the primary byproducts of the biological activity. Secondary treatment is standard in wastewater treatment plants in the U.S.; tertiary treatment is not, though nutrient removal through tertiary treatment is becoming increasingly common. Tertiary treatment uses additional biological or chemical processes to remove nutrients and other contaminants that are not well managed by primary and secondary treatment processes.[1,12]

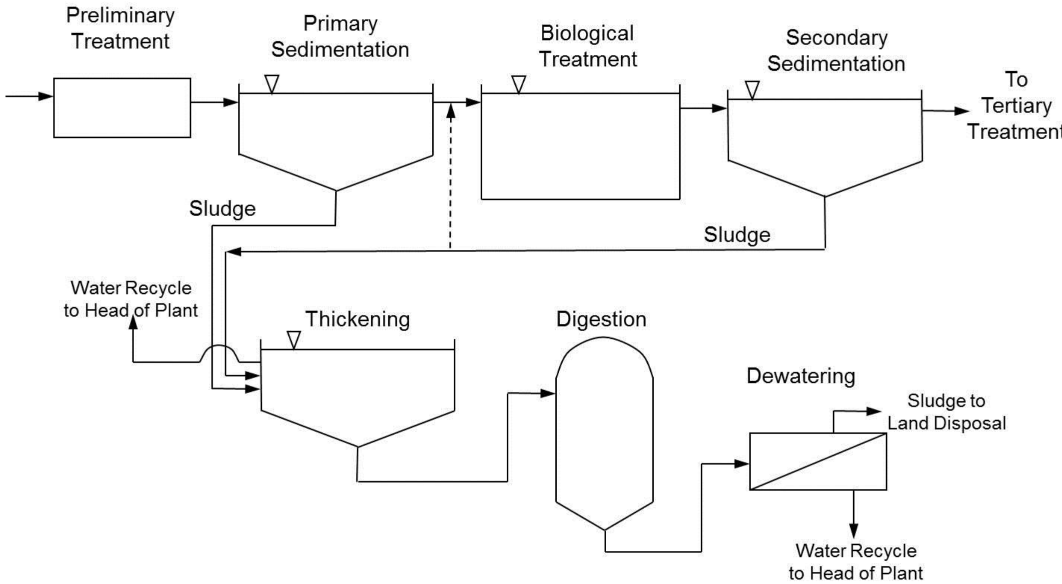

Figure 2.2. Wastewater treatment plant schematic[13]

Locations with special removal needs, such as sensitive coastal environments with nitrogen pollution (*e.g.*, Cape Cod), are likely to include tertiary treatment in their wastewater facilities. Primary treatment removes approximately 5-10% of total nitrogen and secondary treatment removes approximately 10-30% of total nitrogen as some nitrogen is assimilated into cells during biological treatment processes.[1] Additional processes to remove nitrogen include biological nitrification followed by denitrification, which can remove up to 95% of total nitrogen, breakpoint chlorination, which can remove as much total nitrogen as nitrification/denitrification, and the growing and harvesting of algae that assimilate nitrogen, which can remove up to 80% of total nitrogen.[1] Physical operations also can remove nitrogen from wastewater: air stripping of ammonia removes approximately 50-90% but is energy intensive and kinetically quite slow, and reverse osmosis removes 80-90% of total nitrogen.[1] Of all these possibilities, biological nitrification and denitrification are the most common.

Solids that are separated from the wastewater, known as sludge, residuals, or biosolids, must be further treated before they can be released for disposal. Typical solids operations include physical thickening and dewatering as well as biological digestion. Thickening and dewatering reduce the liquid content of the sludge so that the volume and weight of the final product are reduced, facilitating transport and disposal; liquid removed from the sludge is recycled to the head of the plant and treated. Biological solids digestion, in an anaerobic digester, also reduces the sludge mass; more importantly, it stabilizes the solids by converting organic matter into biomass and reducing pathogen content.[1]

Wastewater treatment plants generate both liquid and solid products that must be disposed of after treatment is complete. Liquid effluents are commonly discharged into surface waters, though various types of reuse projects are becoming more common. Reuse always involves tertiary treatment of the wastewater, and the extent of that treatment depends on the ultimate use of the water. For example, if the final use is for lawn and golf course irrigation, tertiary treatment is likely to include only disinfection and granular media filtration. However, if the final use is for drinking water, further removal of metals, recalcitrant organics, and pathogens that are not easily disinfected by conventional means (*e.g.*, *Cryptosporidium*) is undertaken, and numerous treatment process are employed. In indirect potable reuse, effluent of this tertiary treatment is mixed with a natural water (*e.g.*, pumped into an aquifer) that is subsequently treated and used for drinking water; in direct potable reuse, that effluent is pumped directly to the headworks of a drinking water treatment plant and treated along with any incoming natural source water.

Options for solids disposal from wastewater treatment plants depend on the level of treatment the solids have received: Class A biosolids are wastewater solids that have been treated until pathogens are reduced below detectable levels, Class B biosolids have reduced land application potential because they have detectable quantities of pathogens remaining, and other solid residuals are typically landfilled. Incineration of sludge is becoming less common as air pollution regulations increase. Reuse opportunities for residuals of all kinds are increasingly sought as options for disposal are limited and as recognition grows that “closed loops” that regard wastes as resources are critical to increasing the ability of human civilization to sustain itself.[1,12]

Wastewater is transported to treatment plants through sewer collection networks: gravity sewers dedicated to carrying wastewater are the most common type in the U.S.,[14] though some sewers operate under pressure or a vacuum, and many older, urban areas have combined sewers that carry both sewage and stormwater. Flow through conventional sewers is primarily under gravity, but pump or lift stations are often needed in select locations to lift wastewater from a low point in a collection system up to a treatment plant intake or the continuation of the sewer system at a higher elevation. Leaky sewers are problematic. Untreated wastewater can leak out and contaminate groundwater (called exfiltration). Infiltration and inflow of clear water into sewer pipes – from groundwater, stormwater, and cross-connected pipes – can increase the load at the treatment plant. Wastewater in transit through sewer pipes releases gases, including hydrogen sulfide, methane, and nitrous oxide; while the problem of hydrogen sulfide in sewers has been under study for some time, methane and nitrous oxide in sewers are the subjects of more recent and current research.[14–19]

A single sewer system designed to carry both wastewater and stormwater is called a combined sewer. These systems are no longer constructed in the U.S., but they are common in older cities. Even though locations with combined sewers intentionally combined the sewage and stormwater in a single conduit system, they typically did not construct facilities adequate to treat peak combined flows because of prohibitive costs. Therefore, combined sewers are problematic because mixing sewage (containing pathogens and other contaminants) with the large amount of runoff from a precipitation event creates a wastewater flow that can overwhelm existing treatment facilities, thereby reducing treatment effectiveness or even flooding or damaging the plant. Historically, the problem of overflow during and after a storm was solved by simply releasing some amount of the combined flow – including the raw sewage component – directly into a receiving water without treatment. However, as water quality standards have become more stringent, this solution is no longer a viable option. Therefore, many cities face difficult decisions to choose among expensive options for preventing combined sewer overflows (CSOs) from entering receiving waters without any treatment.[1]

Alternative Household Sanitation Systems

Conventional septic systems and centralized treatment are not the only two household sanitation systems available in the U.S. today. Alternatives range from adaptations of these systems (*e.g.*, innovative/advanced septic systems) to toilet systems that re-envision how human waste is managed. In many cases, wastewater from different sources is separated into blackwater, which contains toilet waste, and greywater, which is wastewater from all other household sources such as sinks, showers, and clothes washers. This separation is useful because different contaminants prevail in each of these streams: blackwater contains most of the household pathogen load, as well as much of the nutrient and pharmaceutical content of typical household wastewater, so keeping it separate prevents the contamination of the larger wastewater volume coming from non-toilet water uses in the home.[20,21] Another justification for separating greywater is that blackwater digestion has been proposed as part of a "sustainable" approach to wastewater that can take advantage of the ease of recycling greywater onsite for nonpotable uses. All of the technologies described below, whether or not they separate blackwater from greywater, are based on the idea that treating wastewater closer to its source is likely to be less resource-intensive than transporting all of the wastewater from a large community to a single, central treatment plant.

Innovative/Advanced Septic Systems

Innovative or advanced septic systems (I/A septic) are onsite wastewater treatment alternatives to a conventional septic tank with a soil drainage field. Such systems are typically installed when "difficult site conditions"[1] are present, such as soil unsuitable for a standard drainage field or a local environment that is especially sensitive to certain wastewater constituents (*e.g.*, a coastal area suffering from nutrient pollution). In such cases, additional treatment processes are often added between the septic tank and the ultimate release of effluent into the environment, such as aerobic suspended or fixed-film bioreactors.[1,6] Figure 2.3 shows one example of an I/A septic system.

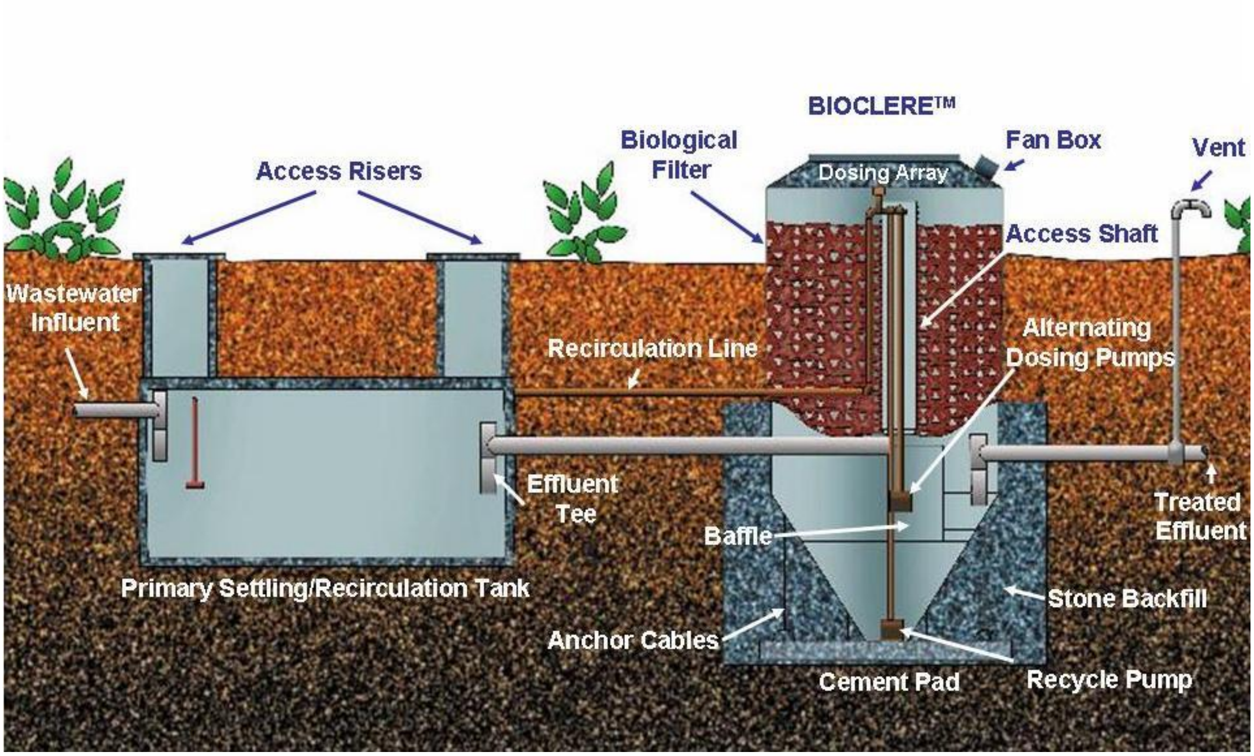

Figure 2.3. Example of I/A septic system.[22]

Four systems considered in the following chapters are proprietary versions of these processes sold as package plants: Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics. Advantex, Bioclere, and FAST systems all use recirculating fixed-film reactors to provide additional treatment[23-25] while the Singulair system uses a suspended-growth aerobic reactor.[26] Fixed-film bioreactors take advantage of biofilm microorganisms that adhere to the filter media; suspended and dissolved organic matter in the wastewater is sorbed by this biological film and oxidized. As time passes, the accumulated organic matter, including biomass, will slough from the filter media and exit the reactor with the wastewater flow, requiring additional clarification following the filter. Recirculation of effluent through such reactors is useful for nitrogen removal from wastewaters because it provides an aerobic/anoxic cycle as the effluent returns from the aerobic filter to the anoxic septic tank (or other settling chamber) and then to the filter again: nitrification of ammonium to nitrate occurs under aerobic conditions and denitrification of nitrate to nitrogen gas occurs under anoxic conditions. Suspended-growth reactors similarly offer biological degradation of organic matter, using a different mechanism to again take advantage of the microorganisms in the sludge produced by the treatment process: sludge is recycled from the final clarifier into the aeration chamber, where aeration and mixing must both be provided (mixing typically provided by the aeration mechanism) to allow for adequate contact between the microorganisms and the suspended and dissolved organics. This process is a small-scale version of the activated sludge process found in centralized treatment plants.[6,8] All I/A septic systems are intended to increase the level of treatment beyond what can be provided by a conventional anaerobic system tank; I/A systems have been shown to perform better than conventional systems on various metrics, but they cannot always meet stringent performance goals, such as low levels of nitrogen in effluent (< 10 mg/L).[27] They also require (considerably) more maintenance and oversight than do conventional septic systems to ensure proper functioning.[6,28]

Anaerobic Blackwater Digesters

Anaerobic blackwater digestion converts the organic matter in human waste into biogas (primarily methane and carbon dioxide) that can be used as an energy source. Biogas production depends not only on high carbon content in the substrate but on a carbon to nitrogen ratio well-suited to methanogenic bacteria; various literature sources differ on the optimal ratio but the range is generally cited as 15:1 to 30:1.[29-32] While including greywater in the digestion process would increase the organic mass and potentially improve the carbon to nitrogen ratio, restricting the flow to the blackwater alone reduces the required volume of the reactor, which in turn reduces the construction costs and decreases the volume of end product that must be managed. In addition to biogas, the digestion process also generates a nutrient-rich slurry with reduced (though nonzero) pathogen content. Including less water content in this slurry reduces the costs of transporting it to a final disposal location, which ideally would be for land application as a soil amendment. In some cases, other solid organic wastes such as kitchen and lawn wastes are added to the digester input to increase the carbon content without increasing the liquid volume.[8,29-32] Figure 2.4 illustrates the components of an anaerobic digester system.

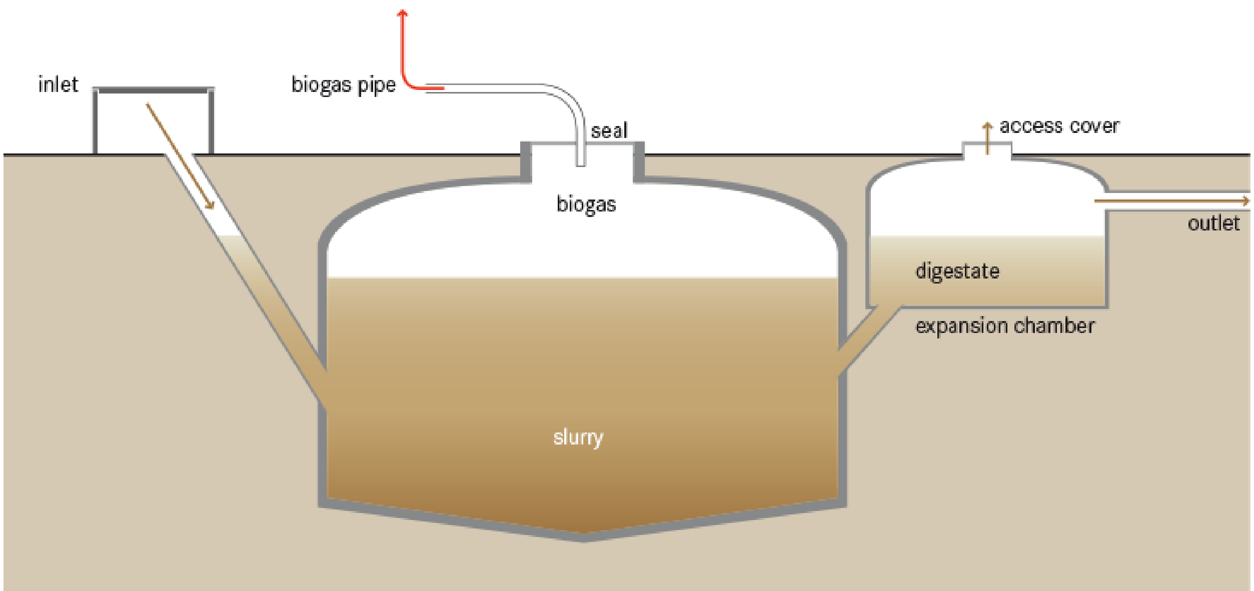

Figure 2.4. Illustration of anaerobic digester system.[33]

Composting Toilets

Composting toilets remove human waste from the household wastewater stream entirely. Though many variations on the composting toilet exist, they all function on the same basic principles: feces are collected in a relatively dry environment and a composting process – biodegradation of organic wastes – is used to inactivate pathogens before the compost is disposed of or used as a beneficial soil amendment. Urine might or might not be collected along with the feces (see discussion of urine-diversion toilets below); biodegradation might be due to thermophilic temperatures (most common) or to the inclusion of worms in the compost pile; and the design of the apparatus used for collection and processing can vary from a seat over a bucket to an advanced system with automatic turning of the compost pile, electric fans to vent odors and evaporate liquids, and the ability to accommodate multiple toilets on multiple floors of a home, such as that shown in Figure 2.5. Composting toilets typically require the addition of a bulking agent, such as wood chips, along with each waste deposition to help with aeration of the pile; aeration and appropriate moisture level are critical for sustaining biological activity and raising the compost pile to thermophilic temperatures for pathogen deactivation. Anaerobic composting is also possible, but it leads to methane production and unpleasant odors. The broader term "dry toilet" encompasses composting toilets as well as toilets that are similar in design but depend on desiccation of feces for pathogen inactivation. Sometimes toilets designed for composting actually function as desiccating toilets because of the dryness of the local environment.[30-32,34,35]

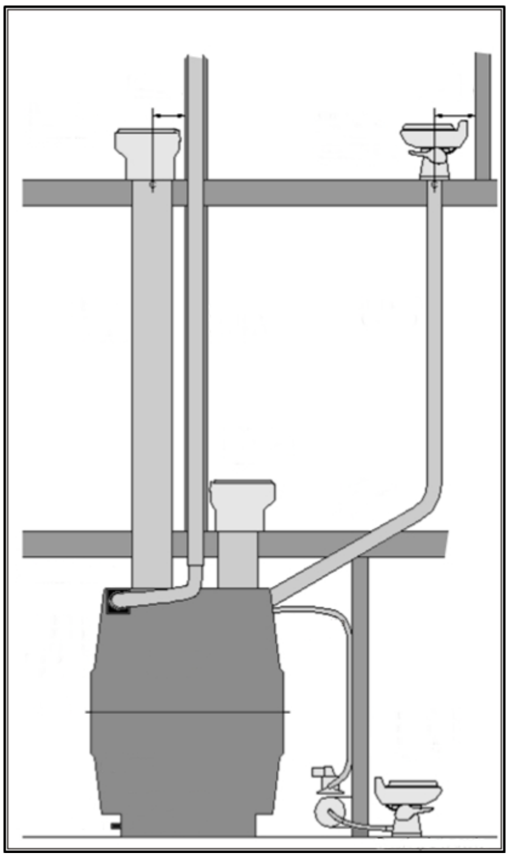

Figure 2.5. Composting toilet system schematic.[36]

Composting toilets have long been used in remote locations in the U.S., such as trailheads, and they are frequently recommended for use in developing countries where funds are unavailable for more capital-intensive human waste management and particularly where water supplies will not support water-based sewage management. They are uncommon in most homes in the U.S., in part because of operation and maintenance requirements. (Other possible reasons for their unpopularity are explored in Chapter 5.) Compost must be removed from the unit, with the time between emptying dependent upon usage and other factors, and it must be disposed of in some manner. Advocates of composting toilets typically recommend using the compost as a beneficial soil amendment for gardens or crops, but it generally requires additional treatment (potentially extended composting or co-composting with other organic wastes) before it is safe to use on crops, especially any crops intended for human consumption. Home composting toilet units typically cannot achieve the thermophilic temperatures needed for adequate pathogen inactivation, mostly because of the relatively small size of the pile. Advantages include the possibility of using the compost as a soil amendment, if the level of treatment is sufficient, displacing manufactured mineral fertilizers. Composting also removes human waste from the wastewater stream: flushing feces down the toilet effectively contaminates a large volume of water with the pathogens and nutrients that originate in a small volume of waste, which can instead be sequestered and thus prevent the need for removing these contaminants from the water at the treatment plant. Removing human waste from the wastewater stream also saves on the water that would be used for flushing.[31,32,37-40]

Urine-Diversion Toilets

Urine-diversion toilets are defined by the separation of urine and feces at the toilet using a divided toilet bowl, as shown in Figure 2.6. From there, feces could be collected in a composting container or flushed to a sewer or septic system while urine is collected in a tank for use as fertilizer. The collection tank can be as simple as a watertight container that sits below the toilet, or it can be as advanced as a tank buried in the yard, similar to a septic tank. A very small volume of flush water might be used to help rinse the urine into the tank.[41-43] Currently, U.S. regulations on the disposal and reuse of sewage sludge do not include any mention of urine, so urine-derived fertilizers cannot be sold until regulations have been decided.[44] However, the beneficial use of urine is a primary goal of urine separation, though separation is also useful for dry toilets that depend on desiccation for treatment of feces because it reduces the liquid content in the waste pile. Most of the nutrient content in household wastewater, especially in the absence of phosphorus-based detergents, is found in urine.[42,45-49] Urine also typically has minimal pathogen content.[47-49] Therefore, separating urine from both feces and the rest of the household wastewater stream preserves a product that requires little treatment before it can be used as a fertilizer, displacing mineral fertilizers. Urine can simply be stored for a period of time to allow pathogen inactivation due to the ammonia content, or it can be pasteurized before use. Urine can then be applied as a liquid or solid fertilizer, allowing struvite to precipitate from the liquid.[41-49] The details of storage, treatment, and distribution would need to be arranged before urine could be widely reused in this way.

Figure 2.6. Urine-diversion toilet with divided bowl.[50]

Some practical and technical difficulties of urine diversion have yet to be overcome. The split bowl requires men to sit while urinating, unless a separate waterless urinal is available.

Everyone must learn to use the split bowl appropriately to reduce cross-contamination between the collected urine and feces, and this is sometimes difficult for young children (smaller divided seats for children are available). In addition to these logistical problems, the piping that carries urine is typically small in diameter and easily becomes clogged with precipitated struvite and hydroxyapatite (or its precursor, octacalcium phosphate), so that frequent cleaning and maintenance are required for proper system functioning.[46,49-53]

SUSTAINABILITY, INTERDISCIPLINARITY, AND LIMITATIONS

Decentralized household sanitation alternatives, such as those discussed above, are often touted as more "sustainable" options because they can cause less environmental pollution than do conventional septic systems or centralized WWTP systems and they typically cost less than centralized systems with their expensive sewer networks. However, before sustainability can be assessed, it must be defined, and specific criteria must be chosen for measuring it. Given the complexity of sustainability, these criteria are spread across many disciplines, so that assessing sustainability within a single disciplinary silo does not make much sense. Given the vast array of criteria that must be met to call any technology truly sustainable, assessing any technology on all criteria is likely to be infeasible, especially for near-term solutions to urgent problems.

The terms *interdisciplinary*, *multidisciplinary*, and *transdisciplinary* have become popular in sustainability literature. A theme in such literature is illustrated by the definition of transdisciplinary work in Costanza *et al.*[54] as "focusing more directly on the problems, rather than the particular intellectual tools and models used to solve them, and by ignoring arbitrary intellectual turf boundaries." Cross-disciplinary approaches bring a multitude of methods to bear on complex problems and might need to develop further methods that inherently transcend boundaries to address the complexity of multidimensional issues more thoroughly.[55,56]

In spite of the wealth of literature exhorting researchers to take up cross-disciplinary arms against the problems of our unsustainable world, concrete examples of such work being done in the sanitation space are few. The Novaquatis project in Switzerland[57] took a multidisciplinary approach to assessing urine-diversion technology, incorporating various aspects of technological and sociological issues. Cordova's[58] investigation of composting toilets in use in several Mexican cities employed an action research approach, which is considered transdisciplinary in its conjunction of "behavioral researchers, community members and policy makers."[59] Other examples can be found of interdisciplinary sanitation research in developing countries,[60] but few studies examine sanitation in industrialized nations from a multidisciplinary perspective.

Hirsch Hadorn *et al.*[55] contend that "If more sustainable options are to be promoted, the following questions have to be addressed jointly: What are more sustainable practices? What are the conditions that might keep people from adopting more sustainable practices and what are conditions that might support them in adopting such practices? Are there effective strategies to overcome these restrictions?" The three stages examined in this dissertation grapple primarily with the second of these questions, providing new building blocks in the body of knowledge that can be used to construct more sustainable wastewater management systems. Although cross-disciplinary research is challenging,[61,62] "there is an ever-increasing call for transdisciplinary approaches to tackle fundamental societal challenges, especially those related to sustainability."[63]

As mentioned above, addressing all sustainability criteria simultaneously is extremely difficult because of the vast number of factors that must be considered. In this dissertation, boundaries are drawn to make the problem tractable, but these boundaries intrinsically limit how fully the results address sustainability. For example, geographic boundaries are drawn around the case study locations (discussed further in subsequent chapters), and the sustainability of any impacts outside these geographic areas are not considered. Nutrient-rich wastes are assumed to be transported to watersheds that will not be negatively affected by the influx; possible shifts from water pollution to air pollution are not examined. Ideally, the boundaries of any such study would be drawn more broadly than they have been drawn for this dissertation, but availability of resources often dictates the limits of the work, as it has here. Future research can and should expand on the findings of this dissertation to achieve a more sustainable assessment of household sanitation technologies. The primary goal of this dissertation is to demonstrate how evaluations of "sustainable" technologies change as more aspects of sustainability are included and to increase understanding of the potential sustainability of household sanitation systems.

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Chapter 3: Cost-Effectiveness of Nitrogen Mitigation by Alternative Household Wastewater Management Technologies[2]

INTRODUCTION

Nutrients such as nitrogen tend to lead to eutrophication issues when they are released into waterbodies as constituents of wastewater streams.[1] Their beneficial action in agricultural applications is exactly what makes large quantities of them undesirable in natural waters, where they cause cyanobacterial and algal blooms: in addition to causing problems of reduced water clarity, taste, odor, and cyanotoxins in drinking water, these blooms lead to losses of dissolved oxygen overnight and during their biodegradation, all of which can significantly diminish water quality and ecosystem services. Eutrophication is the primary reason that nitrogen must not be released into waterways in large quantities.

One example of excessive nitrogen pollution is in Falmouth, Massachusetts, a town of approximately 30,000 people on Cape Cod.[2] Approximately 94 to 96% of the homes in Falmouth use septic systems to manage their household wastewater.[3,4] These septic systems, along with other sources, allow nitrogen to reach the nearby coastal waters in quantities exceeding federal limits for water quality.[5] The problem is exacerbated by the sandy soils and high water table of Cape Cod, a situation that allows nitrogen-containing groundwater to flow easily into surface waters. Falmouth is seeking to reduce the amount of nitrogen released into sensitive coastal waters and thus to mitigate the eutrophication problem, which has impacted aquatic life and fisheries and might well negatively impact tourism, a major local industry. To reach nutrient targets, set as total maximum daily loads (TMDLs), controllable nitrogen loads must be reduced by as much as 83% in some sub-basins; "septic system sources of nitrogen are the largest controllable sources" in Falmouth, so improving household wastewater management is crucial.[5]

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[2] Adapted from Wood, A.; Blackhurst, M.; Hawkins, T.; Xue, X.; Ashbolt, N.; Garland, J. Cost-Effectiveness of Nitrogen Mitigation by Alternative Household Wastewater Management Technologies. J. Environ. Manage. 2015, 150 (1), 344–354.
Wood was primary author and Blackhurst primary editor. Research was completed by Wood with significant support from Blackhurst. Hawkins and Ashbolt set the initial direction of the research and provided support throughout. Xue provided ancillary research support and reviewed the paper.

Literature detailing the flow of nitrogen through households and municipal wastewater systems is scant, even though as much as 63% of nitrogen entering sensitive coastal systems in the northeastern U.S. comes from sewage wastewater.[6] Existing literature primarily focuses on the sources and paths of nitrogen flowing through the environment outside of the household sphere,[7–11] and on the consequences of nitrogen pollution in waterbodies.[12–15] Some literature is dedicated to the flow of nitrogen through conventional municipal wastewater treatment at the system scale.[16–18] Baker *et al.*[19] detail nitrogen flows at the household level including various nitrogen-containing streams other than wastewater, such as lawn fertilizers and vehicle emissions, but the study does not further disaggregate sewage streams for the consideration of alternative wastewater treatment technologies.

Alternative treatment technologies might play important roles in mitigating nitrogen pollution. In addition to centralized solutions such as large wastewater treatment plants (WWTPs), there are *satellite* or *cluster* solutions that typically treat wastewater from neighborhoods rather than from whole towns, and *decentralized* solutions such as septic systems that are installed on each property where waste is produced. Conventional centralized treatment with gravity sewers (referred to collectively as "centralized treatment") is often assumed to be the best or only viable alternative to problematic septic systems, but centralized systems are expensive. In Falmouth, for example, estimated centralized system costs led the town to consider alternative treatment options.[20]

Literature on cluster and decentralized wastewater treatment systems primarily focuses on aspects other than the flow of nitrogen. For example, energy implications[21,22] and nutrient recovery potential[23,24] are explored. Hill and Baldwin[25] consider the advantages of vermicomposting over other methods for composting toilet waste. Studies on the costs of alternative treatment systems[26,27] complement the body of literature on the costs of centralized wastewater treatment.[28–33]

Decision makers seeking to implement nitrogen mitigation strategies need information on the nitrogen mitigation potential of a range of technological options along with the costs and other implications of these technologies, many of which have not been deployed in the U.S. beyond isolated test cases or remote locations lacking infrastructure. Studies on the watersheds of Narragansett Bay, RI[34,35] and Chesapeake Bay, MD[36–38] have combined cost and nitrogen data on large scales, focusing on agricultural fertilizers and wastes and conventional wastewater treatment options. A Barnstable County (MA) Wastewater Cost Task Force has similarly examined the costs and nitrogen mitigation potential of a few treatment systems at the scale of the county.[39] Meinzinger considers a wider range of treatment technologies, including alternative management of rainwater and organic solid wastes, along with the cycling of nutrients from an urban area to fertilize enough agricultural land to supply that urban population with food.[23]

In the current study, we examine both household nitrogen flows and the total system costs of a variety of municipal wastewater treatment technologies to further inform decision makers considering unconventional wastewater treatment technologies. We focus on the cost-effectiveness of nitrogen removal and life cycle costs as part of a larger project that also examines the energy, global warming, and pathogen implications and system resilience.[22,40] We use the household scale as “a socially meaningful and practical unit of measurement”[19] and include technologies that are not common in the U.S., along with options that are currently widespread or gaining popularity. We apply our cost and nitrogen models to Falmouth, MA as a case study of a coastal U.S. town facing a nitrogen pollution problem. We address two key questions:

1. What are the total costs, nitrogen mitigation potential, and cost-effectiveness of a range of conventional and alternative municipal wastewater treatment technologies?
2. What uncertainties influence these outcomes and how can we improve our understanding of these technologies?

METHODS

Technology Selection and Nitrogen Management

Table 3.1 shows the technologies included in the analysis. With the exception of centralized collection and treatment and advanced septic systems (innovative/advanced, or I/A, septic), the technologies listed in Table 3.1 do not treat all household wastewater streams: urine, feces, and greywater (effluent from sinks, showers, clothes washers). To manage all of these streams, discrete technologies were assembled into the combinations indicated in Table 3.1. As summarized in the table, greywater can be managed using either a conventional septic system or an on-site treatment system that allows for reuse as nonpotable water, which we call a greywater recycling system.

Table 3.1. Technology packages to manage urine, feces, and household greywater

Technology Combination	Wastewater Streams		
	Urine	Feces	Greywater
1	Gravity sewers with centralized treatment (referred to as "WWTP")		
2	Advanced septic system		
3	Flush urine-diversion toilet (feces flushed)	+ Conventional septic system	
4	Dry urine-diversion toilet (with compost compartment for feces)		+ Conventional septic system
5			+ Greywater recycling
6	Composting toilet		+ Conventional septic system
7			+ Greywater recycling system
8	Blackwater digester		+ Conventional septic system
9			+ Greywater recycling system

Any nitrogen remaining within the watershed after treatment might eventually contribute to the pollution problem through stormwater runoff or atmospheric deposition. We thus consider a kilogram of nitrogen "mitigated" when it is physically removed from the watershed. This can occur through active transportation of wastes out of the watershed or biochemical conversion to inert N_2 gas, a harmless component of Earth's atmosphere. The paths by which nitrogen might remain in the watershed after treatment include atmospheric deposition of reactive volatiles and release of nitrogen-containing liquid effluents directly into the watershed. A small percentage, around 3-8%, of nitrogen in household wastewater resides in the greywater stream;[23,41] because this is a small contribution and because our focus is on managing household sewage, the nitrogen content of greywater and the nitrogen mitigation potential of greywater management technologies are outside the scope of this paper.

Most nitrogen flow values are reported as milligrams per liter (mg/L): these concentrations refer to conventional wastewater diluted by flush water from a standard toilet. However, the amount of nitrogen excreted by humans is typically reported as a mass per time and for some of the technologies considered here the dilution volume will vary while for others, namely composting toilets, it is nonsensical to discuss an aqueous concentration of nitrogen. We therefore converted flows of nitrogen given in mg/L to flows in kilograms per person per year ($kg\ c^{-1}\ y^{-1}$), using as the dilution volume the amount of water used by a household with standard flush toilets (approximately 265 $L\ c^{-1}\ d^{-1}$).[42]

For this analysis, we draw from disparate studies that partially characterize household flows to estimate a complete mass balance of nitrogen for our alternative technologies. Meinzinger[23] and Baker *et al.*[19] estimate the total quantity of nitrogen in human waste and its partitioning between urine and feces that we take as our base case. The nitrogen flows in WWTP effluent were taken from Gerardi.[43] Data on volatilization of N_2O in sewer systems came from Short *et al.*[18]

All nitrogen flow data for I/A septic systems came from the Barnstable County Department of Health and the Environment, which has collected performance data on over 1,500 systems installed on properties around Cape Cod; they publish median, minimum, maximum, and upper and lower quartiles of the nitrogen concentration in liquid effluent from each installation. We used the median values from all installations of the four I/A brands that are currently most popular on Cape Cod and that meet septic performance standards: Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics. For our base case, we averaged the values from all installations of these four systems. The range explored in the sensitivity analysis is plus and minus 50% of the base case value, which is approximately the standard deviation of the published summary statistics.[44]

In the absence of empirical values for discrete nitrogen flows, we used mass balance calculations to find the quantities of nitrogen in compost and urine collected from eco-toilets and the quantity of N_2 that volatilizes during treatment at a WWTP. Our assumptions about volatilization of nitrogen include (1) no nitrogen compounds other than ammonia will volatilize from collected compost or urine during storage, transport, or treatment; (2) ammonia volatilization from stored urine is independent of the time of storage and so can be conceptualized as occurring entirely during the storage phase (not the transport phase); (3) the volatilization of ammonia from stored compost from composting toilets is the same as from stored urine; (4) 100% of volatilized reactive nitrogen compounds will be re-deposited within the watershed (base case); and (5) there is no volatilization of any nitrogen compounds in pressure or vacuum sewers, because these are designed to have no headspace (completely full pipes) and thus there is no opportunity for volatilization. Negligible to no N_2 volatilizes during composting and urine diversion, due to lack of anoxic conditions needed for denitrification, nor from blackwater digestion.[45–47] Thus nitrogen is mitigated in these systems by physical removal from the watershed, which we assume is achieved by truck transportation.

Both WWTP and I/A septic system technologies mitigate nitrogen primarily by converting it, through biochemical processes, to N_2. However, both treatments also produce nitrogen-containing residuals: solids in a treatment plant or sludge that is pumped from septic tanks, including those paired with flush diversion toilets. We assume that solids and septage are incinerated, landfilled, or potentially used for agriculture outside the watershed. This assumption is based on current practice in Falmouth, in which the existing treatment facility collects sewage from 4 – 6% of homes and also accepts septage: the septage is nominally dewatered before being combined with solids from wastewater treatment and sent to an incinerator out of state and outside the watershed.[3]

Finally, we assume no other leakage or loss of nitrogen from any wastes during storage, transport, or treatment. The validity of this assumption might be a fruitful avenue for future research, particularly considering potential losses during unusual circumstances such as power outages and floods, as well as leakage from aging conventional sewers.[48] The possibilities for operators' errors (*e.g.*, spills during transport of collected urine) leading to nitrogen leakage into the watershed might also be an important point to consider in the future.

We use sensitivity analysis to address the uncertainties in the underlying data and assumptions. We vary the per capita input of nitrogen to the wastewater system according to ranges found in literature.[49–51] We vary the amounts of nitrogen remaining in the watershed after treatment due to atmospheric deposition of volatiles and release of liquid effluent into the watershed by plus and minus 50% of the base case values. The nitrogen mitigation potential of each system is calculated from these ranges, according to Equation 1, providing a range of mitigation values for each system.

$$N\ input - (volatile\ N + N\ in\ liquid\ effluent) = N\ mitigated\ by\ technology \quad (1)$$

where *N input* is the amount of nitrogen in human waste, *volatile N* is the amount of nitrogen in reactive volatiles that might redeposit within the watershed, and *N in liquid effluent* refers to liquid effluents released into the watershed. We calculate the low case mitigation value using the low case for input and the high cases for volatiles and liquid effluents; we calculate the high case mitigation value using the high case for input and the low cases for volatiles and liquid effluents. Thus *N mitigated by technology* is a measure of how much nitrogen the technology removes from the watershed, not a measure of how effectively it meets mitigation goals.

A summary of all assumed nitrogen flow base case values, ranges, and references can be found in Appendix A.

Total Cost and Cost Effectiveness Analysis

For each technology option, capital and operating cost data were assimilated to estimate equivalent annual costs per typical household as shown in Equation 2.[52]

$$EAC = \sum_{all\ components}\left[capital\ \times q \times \frac{i\,(1+i)^L}{(1+i)^L - 1}\right] + \sum_{all\ components}[O\&M \times q] \quad (2)$$

EAC is equivalent annual cost; *capital* and *O&M* are capital and O&M costs, respectively, of each component of the technology package; q is the number of installations per household of the component; *i* is the discount rate or interest rate; and *L* is the service lifespan of the component. In all cases we assume that the technology has no salvage value and that costs do not increase over time. We do not explicitly consider the possible costs associated with significant failures of any of these systems.

We calculated cost-effectiveness (CE), or dollar per kilogram of nitrogen mitigated, according to Equation 3.

$$CE = \frac{EAC\ of\ technology\ per\ household}{annual\ nitrogen\ mitation\ potential\ of\ technology\ per\ household} \quad (3)$$

We calculated costs both on a per-household basis and scaled to Falmouth's wastewater service area, using sensitivity analysis to examine uncertainty in our assumptions. For our base-case model, we assume each existing household has two conventional toilets serviced by a conventional septic system. We assume all technology swaps occur in "year 0" or immediately. We consider discount rates of 3%, 5% (base case), and 7%.[53] The sources and assumptions underlying all other cost estimates are given in Table 3.2.

Table 3.2. References and assumptions for capital and O&M cost data

Cost Item	Capital Cost References	O&M Cost References	Notes and Assumptions
WWTP and gravity sewers	4,54	39,55	Assumes 100 gallons per person per day, 1.4 people per home in Falmouth.
I/A septic systems	56–62	59,61–63	Includes costs for Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics.
standard toilet	64	assumed	Includes multiple mounting options. O&M assumes one $100 servicing every 10 years for base case, annual $100 servicing for high case, no maintenance for low case.
Urine-diversion toilet	64–67	68, assumed	Includes dry and flush toilet options. Installation costs are 'bare labor.' Assumes 500-gallon urine tank (⅓ of standard septic tank), located outdoors. Flush toilet O&M is ⅔ of septic O&M cost, assuming some fixed costs. Dry toilet O&M comes from flush toilet O&M and compost toilet O&M.
compost toilet	64,69	70,71	Includes dry toilet and foam flush options, two sizes of composter. Installation costs are 'bare labor.' Capital costs are for a pair of toilets with one compost container.
blackwater digesters and pressure or vacuum sewers	26	26	Euros converted to USD at €1 to $1.37. Includes pressure and vacuum sewer network options.

Table 3.2, continued

vacuum toilet	26,72–75	assumed	Euros converted to USD at €1 to $1.37. Installation is 'bare labor.' O&M assumed same as standard toilet.
conventional septic system	64,76	77,78	All new tanks in Massachusetts are required to be 1,500 gallons; some legacy tanks are 1,000 gallons. Assumes annual pumping to be conservative.
retrofitting or upgrading an existing septic system	76,79		Includes using existing tank as-is, upgrading existing tank, filling or removing existing tank and installing a new one.
greywater recycling system	64,80	80	Australian dollars converted to USD at $1AUS to $0.89. Costs for Nubian, Perpetual Water, Clearwater Aquacell, and Rootzone vertical filter systems
variable drinking water supply cost		81,82	Uses rate for excess usage on household bill. Range for sensitivity analysis comes from Falmouth budget line DPW Water Utilities Other Expenses for two years.
decentralized monitoring		assumed	Assumes $70,000 per year for one inspector, 6-10 inspections per day, working 250 days/year.
removal of existing standard toilet	83		

We do not include the costs of any additional treatment or storage of the byproducts of waste treatment for reuse; we do include the cost of transport of waste products for final disposal or use. For a WWTP, I/A septic systems, and eco-toilets, we assume these transport costs are included in the operation and maintenance (O&M) cost estimates given by sources, since disposal is a critical component of O&M in these cases. For blackwater digestion, we explicitly include estimates for the cost of transporting the entire digestate slurry (liquids and solids).

Compared to the WWTP and I/A septic system, the other technologies will incur lower potable water supply costs because less (or no) water is required to flush the toilets in those systems. To estimate the monetary savings from the alternative systems, we used Falmouth's block pricing structure, which includes a fixed base rate and a variable rate that depends on usage.[81] We assumed that the fixed costs are constant across scenarios and used end-use demand estimates.[65,84–87]

A summary of all cost data with references and assumptions can be found in Appendix A.

RESULTS

Nitrogen Flows

Figure 3.1 shows the estimated flows of nitrogen through the five primary household wastewater treatment systems investigated in the study: flush and dry diversion toilets are shown as a single flow. If digestate is physically transported out of the watershed, then blackwater digestion results in 100% mitigation of nitrogen. The nitrogen remaining in the watershed under all other scenarios is from deposition of volatiles and from liquid effluent released into the watershed.

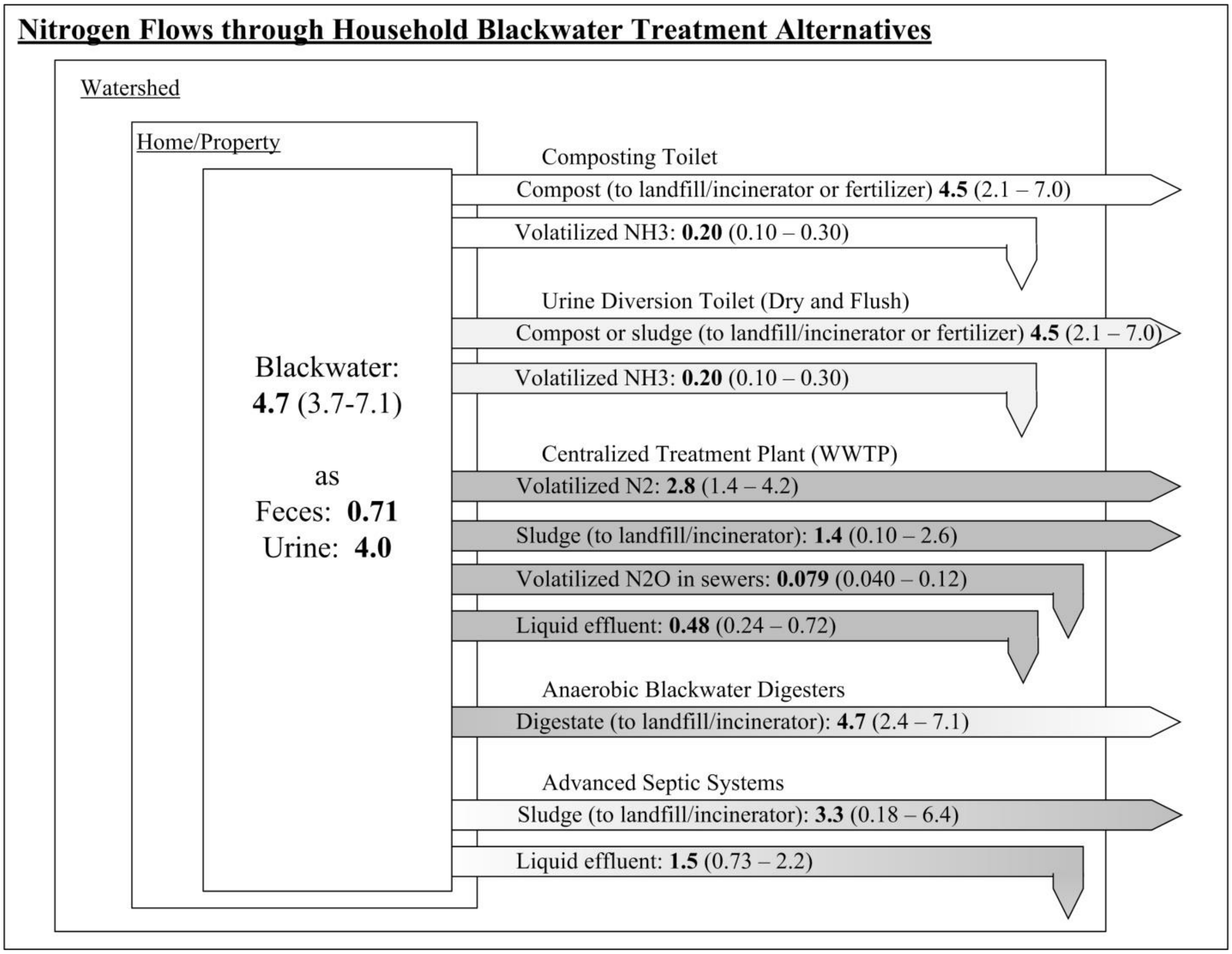

Figure 3.1. Nitrogen flows through household blackwater treatment systems.
Notes: All mass flow values are in units of kilogram of nitrogen per capita per year; base case value is shown in bold, ranges for sensitivity analysis are given in parentheses.

Total Cost and Cost-Effectiveness

For a typical household, we couple the equivalent annual cost estimates (see Equation 2) with the mass balance estimate in Figure 3.1 to estimate the cost-effectiveness of N mitigation. We differentiate between new construction and retrofits of existing homes: existing homes have wastewater systems in place that can be used with some technologies but must be modified or replaced if other technologies are installed, while newly constructed homes will need entirely new systems installed regardless of technology choice, leading to modeling differences in capital costs between the two scenarios. We considered two retrofit cases: a usable existing septic tank and an existing septic tank in need of replacement. For I/A septic systems, the costs for both usable and failing existing septic systems are within the cost range used in the sensitivity analysis. Figure 3.2 shows cost and cost-effectiveness on a per-household basis.

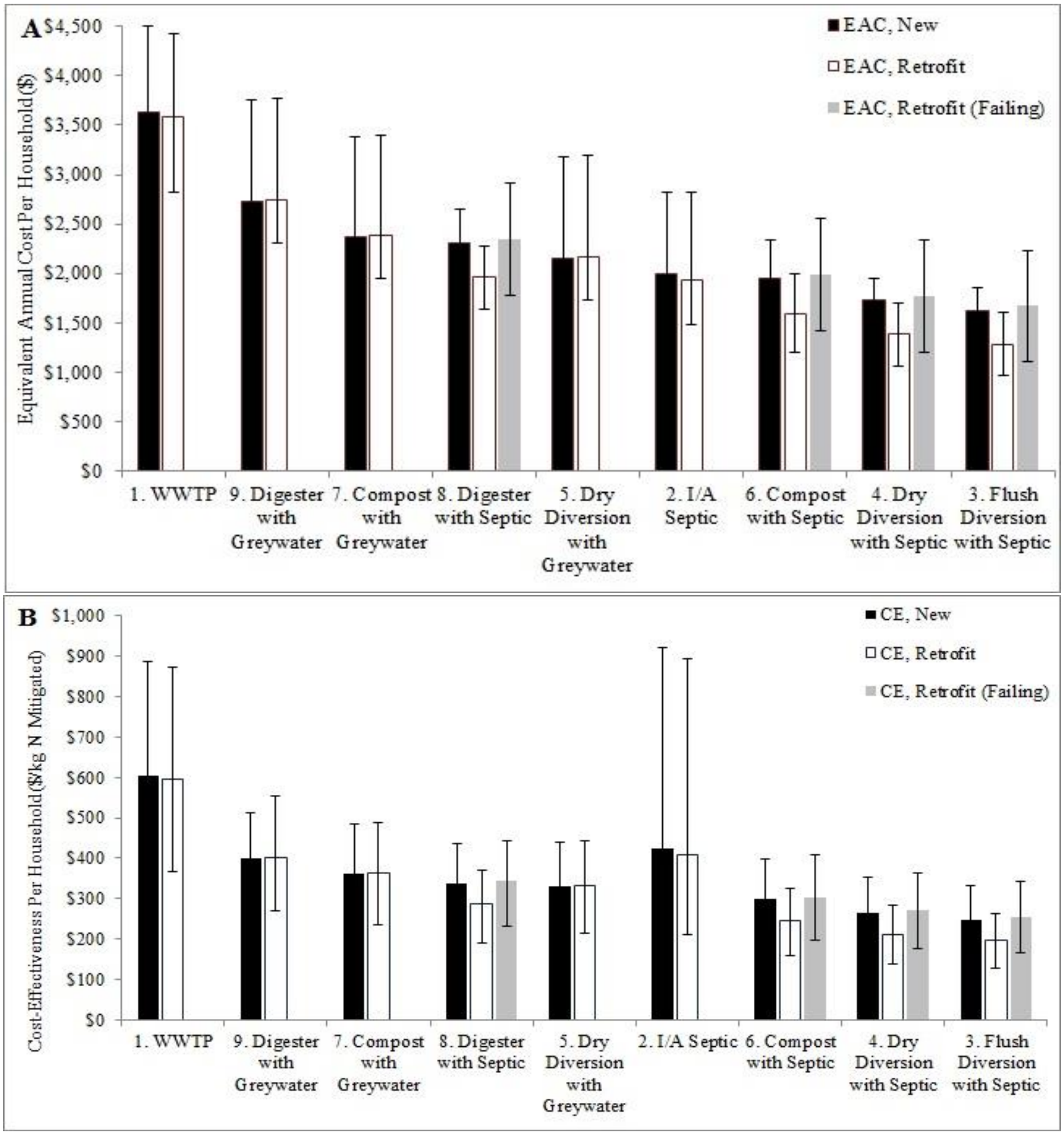

Figure 3.2. (A) Equivalent annual cost and (B) cost-effectiveness of alternative technologies on a per-household basis

Notes: *EAC* is equivalent annual cost; *CE* is cost-effectiveness; *New* is new construction; *Retrofit* is retrofits of existing homes, including those with usable septic tanks and cases in which the existing septic tank is irrelevant; *Retrofit (Failing)* is retrofits of existing homes with failing septic tanks that must be replaced. Error bars show cost range from sensitivity analysis (see Sensitivity Analysis for more detail).

In all cases, the preferred technology – least expensive and most cost-effective (least cost per kilogram of nitrogen mitigated) – is the flush diversion toilet, followed by the dry diversion toilet with conventional septic system for greywater. Composting toilets with conventional septic system are third best in all cases, though I/A septics are very similar in cost for new construction and retrofits of homes with failing septic systems. Blackwater digestion is the most cost-effective option after eco-toilets.

Several technologies are clearly unfavorable. The most expensive and least cost-effective option in all cases is the centralized WWTP. The pairing of a greywater recycling system with any treatment option is always more expensive than a conventional septic system paired with the same treatment technology.

We scaled the per household results in Figure 3.2 to Falmouth's wastewater service area assuming 20% of the homes have failing septic systems, according to data for Massachusetts.[88] Figure 3.3 shows the results for the entire service area, incorporating this assumption. At this scale, the preferred options are still the flush diversion toilet and the dry diversion toilet with conventional septic systems for greywater management. The next least expensive and most cost-effective technology is compost toilet systems with conventional septic treatment of greywater. Blackwater digestion is still the most cost-effective option after eco-toilets.

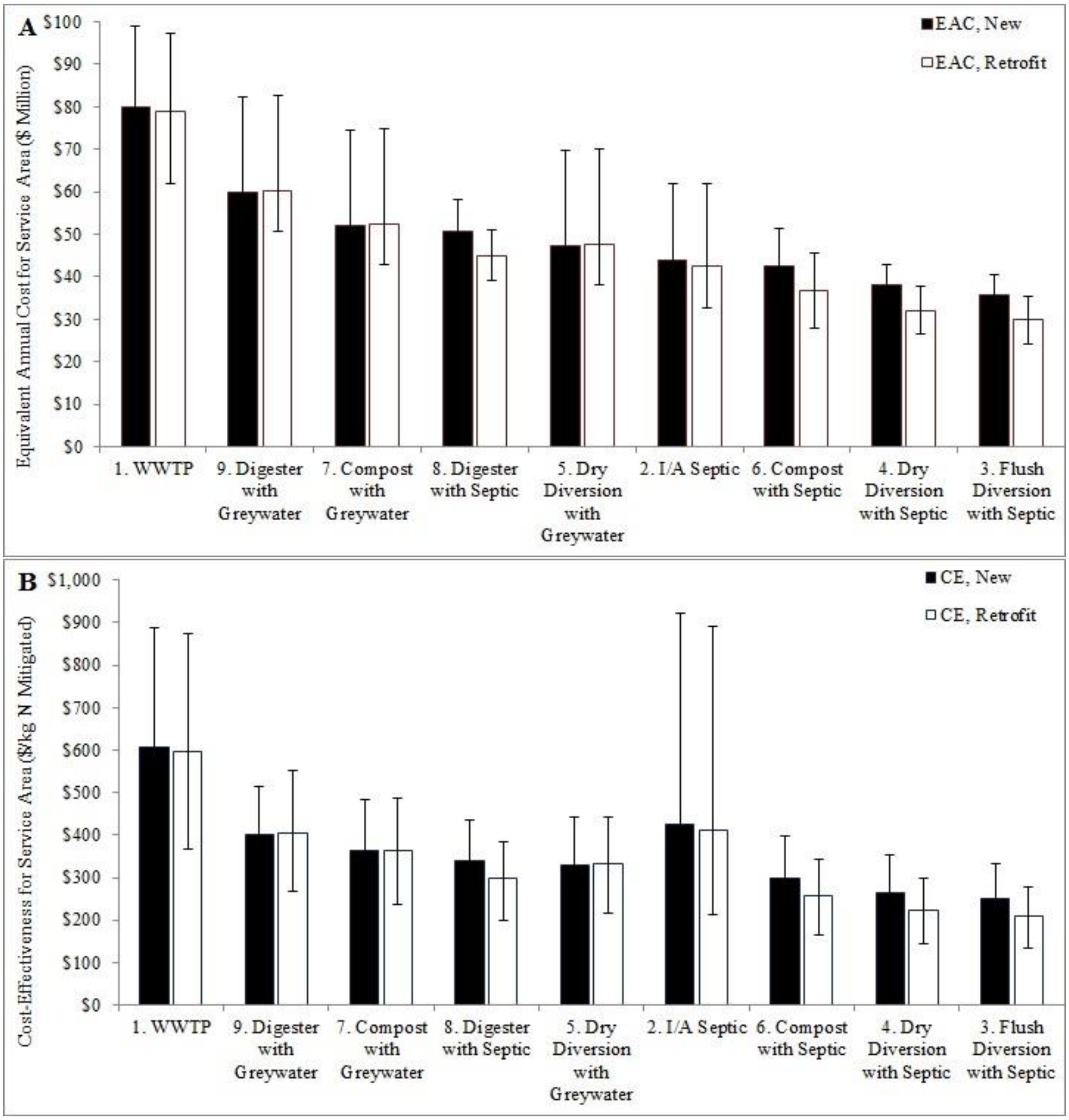

Figure 3.3. (A) Equivalent annual cost and (B) cost-effectiveness of alternative technologies for the entire service area, assuming 20% existing septic systems are failing

Notes: *EAC* is equivalent annual cost; *CE* is cost-effectiveness; *New* is new construction; *Retrofit* is retrofits of existing homes, including those with usable septic tanks and cases in which the existing septic tank is irrelevant; *Retrofit (Failing)* is retrofits of existing homes with failing septic tanks that must be replaced. Error bars show cost range from sensitivity analysis (see Sensitivity Analysis for more detail).

Sensitivity Analysis

For our sensitivity analysis, we include here (Figure 3.4) only a few illustrations of key points in the uncertainty of equivalent annual system cost and cost-effectiveness. Additional sensitivity analysis can be found in Appendix A.

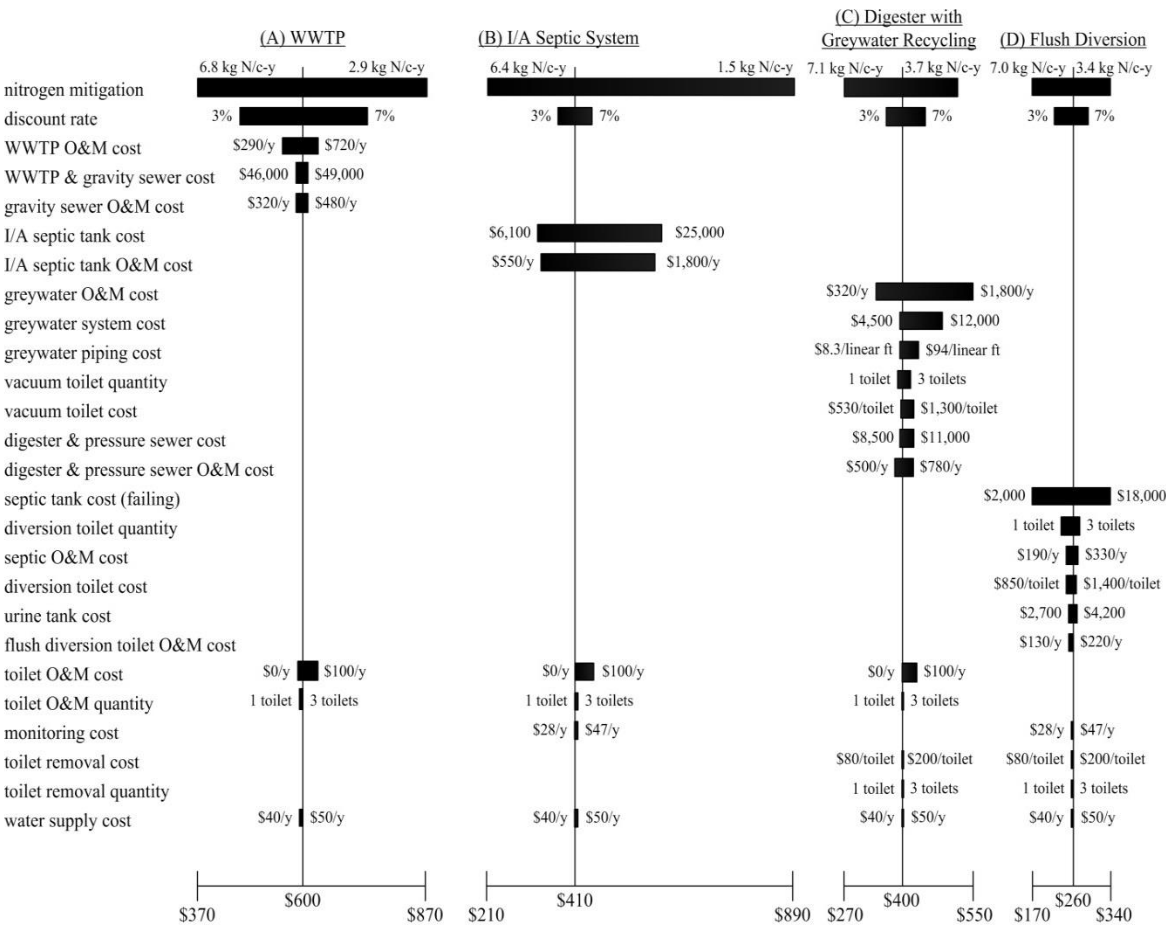

Figure 3.4. Uncertainty for cost-effectiveness, in retrofit case, of (A) WWTP system, (B) I/A septic system, (C) blackwater digester with greywater recycling, and (D) flush diversion toilets with failing existing septic system

Notes: Each bar shows the range of system cost-effectiveness values as one factor ranges between the endpoints shown. Cost factors are all on a per-household basis.

In all cases, nitrogen mitigation is the most uncertain factor in determining cost-effectiveness of a system; for digesters paired with greywater recycling, the O&M cost for greywater recycling is as uncertain as nitrogen mitigation. In all systems incorporating greywater recycling, the capital and O&M costs for greywater recycling are two of the three greatest sources of uncertainty in the cost of the system (*e.g.*, Figure 3.4C). In all retrofit cases employing septic systems, the septic cost is the first or second most important factor affecting uncertainty in system cost (*e.g.*, Figure 3.4B, D). The least uncertain factors in all cases are, as applicable, the cost of water supply, the cost of decentralized monitoring, and the cost of removing existing toilets before installation of eco-toilets or vacuum toilets.

The discount rate's most prominent role is in the equivalent annual cost of the WWTP (Figure 3.4A), followed by its role in the cost of both types of diversion toilet and the blackwater digester paired with conventional septic. For other systems, the discount rate does not contribute to the overall uncertainty as much as other factors (*e.g.*, Figure 3.4B, C, D).

Some options are clearly more expensive than others, even accounting for uncertainty. Over their entire cost ranges, the WWTP is more expensive than any eco-toilet or blackwater digester paired with a septic system for greywater treatment, except in the case of blackwater digestion paired with an existing septic system that is failing and needs replacement, which at its most expensive is similar in cost to a WWTP at its least expensive. In the lowest cost case, the WWTP is about the same cost as I/A septic is in the highest cost case. Similarly, compost toilets or digesters paired with greywater recycling at their least expensive are more costly than, or about the same cost as, the most expensive case for flush and dry diversion toilets paired with septic systems in new construction, and any eco-toilet paired with a usable existing septic tank in the retrofit case. Also in the retrofit case, a flush diversion toilet paired with a usable existing septic system is always cheaper than a dry diversion toilet paired with a greywater recycling system and about the same as or cheaper than a blackwater digester paired with a septic system.

There are fewer mutually exclusive ranges of cost-effectiveness. The WWTP at its most cost-effective (lowest dollar per kilogram of nitrogen mitigated) is less cost-effective than the entire cost-effectiveness range, in the new case, for flush diversion toilets and dry diversion toilets paired with septic systems; in the retrofit case the WWTP is less cost-effective than any eco-toilet or a blackwater digester with a usable existing septic tank, and flush and dry diversion toilets paired with failing existing septic systems.

Discussion

In all cases, we found that the most cost-effective alternatives for mitigating nitrogen are decentralized systems, paired with conventional septic systems as necessary. Sensitivity analysis shows that a WWTP is in no case the preferred option, with centralized systems being at least $40 more per kilogram of nitrogen mitigated than flush diversion toilets, assuming conservative ranges for model inputs, and at best equally cost-effective as the worst-case scenario for other eco-toilets. Sensitivity analysis also shows that flush and dry diversion toilets, paired with septic systems, are preferred in most cases, with other decentralized systems presenting potentially viable options. According to our results, decentralized options paired with greywater recycling systems are generally not as attractive as other options, including short-run reductions in potable water costs associated with greywater recycling. The relative appeal of I/A septic systems is heavily dependent on the cost and the nitrogen mitigation of the specific system installation.

Centralized WWTPs and sewer networks are very expensive in Falmouth, MA, where housing density is relatively low and a coastal geography increases costs. In Falmouth, it might be feasible to sewer certain portions of the town where housing density is currently higher, while employing decentralized technologies in other areas. However, without a highly efficient nutrient reduction technology, ocean discharge might still be problematic. We found that when decentralized technologies are implemented, pairing them with greywater recycling systems increases the package cost without adding nitrogen mitigation benefits, making conventional septic systems preferable for greywater management. However, some homeowners who choose to install decentralized systems might also choose to recycle their greywater to reap environmental benefits other than nitrogen mitigation, so understanding the costs of these systems can be useful.

If Falmouth, MA were to adopt a single solution for wastewater treatment in all homes, the results of this study indicate flush diversion toilets as the preferred option according to equivalent annual cost and cost-effectiveness measures, but flush diversion toilets do not completely eliminate household waste nitrogen from the watershed. All eco-toilets release some nitrogen into the watershed: less than a WWTP or I/A septic systems, but more than blackwater digesters, which release zero nitrogen into the watershed if the digestate slurry is exported. Blackwater digestion systems paired with conventional septic systems are competitive with diversion toilets in cost-effectiveness, within the bounds of uncertainty. Therefore, neighborhood scale blackwater digesters might be a preferred solution to Falmouth's nitrogen pollution problem, while flush diversion toilets are the preferred technology for household wastewater treatment with consideration for nitrogen mitigation, according to our results. If blackwater digesters were chosen for implementation, it would be important to consider other impacts the systems might have, such as emissions from trucking digestate and environmental impacts in the disposal location.

Selection of one or more decentralized technologies would allow for immediate replacement of critical systems and future replacement of systems that are currently functioning adequately. For example, installation of the chosen technology could be mandated at the time of existing septic system failure: since failing conventional septic systems are significant contributors to the environmental problem, replacing systems as they fail would improve the worst sources of the problem. Homes with adequate septic systems could be required to install the new technology by some later date, such as the time of title transfer of the property. In this way, use of decentralized technologies would allow for immediate redress of the most urgent needs while providing additional compliance time in less urgent situations.

In addition, decision-makers could allow individual homeowners to choose which of several decentralized options they prefer to install. Homeowners could install eco-toilets independent of their neighbors' choices; neighborhoods could collectively elect to install blackwater digestion systems. This freedom of choice might also increase acceptance of technological change, whereas a narrow mandate might meet some resistance. Eco-toilets are currently uncommon in U.S. homes, and homeowners might be resistant due to real and perceived operation and maintenance differences relative to conventional toilets. Flush diversion toilets have the advantage of allowing all waste to be stored outside the home, in buried tanks, but they still require "aiming" in the toilet. Blackwater digestion systems operate with vacuum toilets, which offer a similar user experience to standard toilets. I/A septic systems are almost the same as conventional septic systems from the homeowner perspective. For owners considering the future resale value of their properties, more familiar, easy to use toilet systems might be more appealing than novel technologies.

Technologies that allow for resource recovery – both nutrients and biogas – may become more attractive but costs and benefits become less certain. Sale of compost as fertilizer is one of the easier benefits to quantify, since biosolids from wastewater treatment are already included in commercially available products in the U.S.: we estimate the benefits of selling compost to range from about $10 to about $200 per year, per household. Regulations governing the sale of other waste-derived products are currently immature, and the logistics of collection, treatment, and distribution have not yet been established, but a market for recovered resources might alter the decision context in the future.

Other uncertainties that might benefit from further research include household nitrogen flows, mitigation potential of technologies, and cost increases over time, particularly for water and energy. Further work could also improve our understanding of what discount rates are appropriate given anticipated householder preferences and potential financing strategies (*e.g.*, municipal bonding, rate financing) and incentives for adoption (*e.g.*, rebates, rate reductions). If monetary incentives were used for decentralized technologies, then individual discount rates should be used to model technology adoption at the household level and municipal discount rates should be used to model public financing. This could affect the technology adoption rate and ultimate penetration rate, and thus the net cost-effectiveness. The cash flow implications might similarly influence selected technologies. A new WWTP would cost about $1.1 billion in short-term financing. If a decentralized system were chosen, the cash could be spread over a longer time period, reducing the burden of short-term financing.

In any implementation of novel technologies, it is important to remember that there might be unintended or unanticipated consequences. For example, if all homes installed composting toilets and thus drastically reduced their water consumption, the water supply utility might see reduced revenues, increased water age in distribution systems, and other possible effects. Treatment might become less efficient on a per-unit basis, even while becoming more sustainable overall. As with a centralized WWTP, the cost-effectiveness and other measures of efficiency of a centralized potable water utility depend on the local housing density. Researchers exploring these new technologies should do our best to anticipate possible direct and indirect consequences of their use, but we must also watch closely as these technologies are implemented to observe what we could not anticipate.

The ultimate driver in Falmouth, MA and other similarly affected areas is to avoid eutrophication of surface waters. Thus an ideal measure for our study would be technology life cycle cost per eutrophication potential; however, the fate and transport modeling required to support such an analysis is outside the scope of this study. A model that integrates fate and transport with the engineering economic assessment performed herein for a wider array of nitrogen management alternatives would be a powerful tool for eutrophication mitigation.

CONCLUSIONS

We develop a mass balance of nitrogen flow through households and estimate the cost-effectiveness of nitrogen "mitigated" by conventional and alternative household scale wastewater technologies in Falmouth, MA. Across a range of assumptions, we find that flush diversion toilets paired with conventional septic systems are the lowest cost and most cost-effective option for managing nitrogen in household wastewater, with dry diversion toilets paired with conventional septic systems as the second best option. Composting toilets are also attractive options in some cases, particularly best-case nitrogen mitigation; innovative/advanced septic systems designed for high-level nitrogen removal are cost-competitive options for newly constructed homes, except at their most expensive. A centralized wastewater treatment plant is the most expensive and least cost-effective option in all cases. Using a greywater recycling system with any treatment technology increases the cost without adding any nitrogen removal benefits. Sensitivity analysis shows that these results are robust considering a range of cases and uncertainties.

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DISCLAIMER

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Chapter 4: Incentivizing Decentralized Sanitation: *The Role of Discount Rates*[3]

INTRODUCTION

As populations grow and infrastructure ages, many municipalities are grappling with how to sustainably manage the sewage generated by their residents.[1] The two most common household sanitation configurations in the U.S., decentralized septic systems and centralized wastewater treatment plants with sewer collection networks, address key aspects of waste management, but might not adequately address increasingly important challenges such as nutrient pollution or combined sewer overflows (CSOs).[2–5] New technologies are often put forward as improved sanitation solutions, but their viability remains unclear. Such technologies are frequently decentralized, serving a single home or a cluster of homes rather than an entire town, to reduce the need to pump wastewater long distances; such technologies are more technically advanced than conventional septic systems and might be less expensive than sophisticated centralized plants with extensive collection networks.[6–8] However, analyses of these technologies typically include little if any consideration of the decision-making processes of the homeowners who will ultimately either purchase, install, and use them, or reject them.[6–11]

This study considers homeowners and public utilities as two separate decision-makers, both involved in accepting or rejecting a new solution to household sanitation. The public decision process is already well modeled,[12–15] but the factors influencing individuals' adoption of sanitation technologies have not been thoroughly studied. In this study, life cycle costs are calculated from the perspectives of the two decision-makers and compared. The discount rate, a component of life cycle cost, is used to improve the understanding of homeowners' adoption of decentralized sanitation technologies, and the interaction between the private and the public

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[3] Adapted from Wood, A., Blackhurst, M., Garland, J., Lawler, D.F. Incentivizing Decentralized Sanitation: The Role of Discount Rates. *Environmental Science and Technology*. In revision.
Wood was primary researcher and author. Blackhurst suggested initial research direction. Blackhurst and Lawler provided research support and significant editing. Garland provided EPA support and reviewed the paper.

decision is considered in the context of the likely success or failure of monetary incentives to bring the parties into agreement. Specifically, this study addresses two questions:

1. How do life cycle cost comparisons change when individual discount rates are incorporated?

2. How does analysis with individual discount rates help set expectations about the need for and success of adoption incentive programs?

Background

Many disciplines study decision-making processes, and those that focus on individuals and households often find that "individuals do not make consistently rational decisions," with "rational" meaning "having preferences that are ordered, known, invariant, and consistent."[16] A review of nearly 200 published works on decision-making models relevant to energy-efficient household investments and other environmentally-friendly behaviors summarizes findings from a range of disciplines reflecting this lack of consistently "rational" behavior by individuals, with each discipline offering its own examination of the behaviors underlying real decision-making processes.[16] Analysis of adoption decisions for decentralized sanitation systems would be simpler if these complex decision-making processes were omitted, but such analysis is incomplete: incorporating the perspective of household decision-makers is likely to change the apparent viability of some decentralized technologies as solutions to modern sanitation problems.

In analyses of individual or household decision-making, the discount rate is often used to quantify a whole host of consumer preferences not otherwise well incorporated into life cycle cost analysis. The method is based on Samuelson's[17] discounted utility model in which individuals' preferences and biases are combined "into a single parameter, the discount rate."[18] Individuals rarely perform life cycle cost calculations explicitly, but they nevertheless incorporate their preferences regarding time tradeoffs into purchase decisions.[16,19,20] These preferences are quite different for an individual than for a public entity, which is assumed to behave rationally and explicitly balance monetary tradeoffs over time.[19,21] .

Life cycle cost includes both upfront capital and labor costs to install a new system and the operation and maintenance costs over the system's lifespan; this metric allows for fair comparison between systems that have different distributions of costs over time. In such time tradeoff calculations, public utilities use discount rates based on market interest rates or "social" discount rates that are appropriate for low risk, long term investments.[22,23] Such investments reflect how public entities raise and spend money and are discounted at rates relevant to this type of large scale, long term, explicit planning. However, individuals face considerably different constraints and priorities in their financial decision-making, and they tend to use much higher discount rates in their implicit or unconscious cost calculations.[21] Recall that a zero discount rate means that the value of money does not change with time, whereas any positive rate means that a dollar received in the future has less value today than a dollar received today.

Hartman and Doane noted: "The implicit discount rates used by consumers in [consumer-durables] purchases can be expected to include potentially substantial premia for risk, liquidity, and uncertainty...[which] make it inappropriate to assume that a household's implied discount rate is equal to the market rate of interest."[24] Other authors[18,25,26] have also examined the preferences and biases that are often encompassed in the discount rate, including preferences for maintaining an accustomed level of consumption, perceived differences between gains and losses, and mental accounting models that lead consumers to consider different portions of their income as categorically different.

Empirical literature on discount rates in purchases of energy-efficient technologies abounds.[19-21,24-31] Only a single paper has been found that examines implicit discount rates in the sanitation context, as part of a study on latrines in homes in India; the consideration of discount rates is mentioned only briefly, and elicited rates are not reported.[32] Discount rates, however, are important in life cycle cost calculations for sanitation technologies. As Wood *et al.*[8] illustrated, variation in the discount rate is an influential parameter in the life cycle costs of many sanitation technologies, even when the range of rates included is narrow; the influence of the discount rate on the life cycle cost increases as the range of rates widens.

Published cost analyses of decentralized household sanitation systems rarely discuss discount rates, and those that do typically use the same discount rate for both centralized and decentralized systems.[9–11] Any system financed by the municipality, such as a wastewater treatment plant (WWTP), is appropriately evaluated using market-based discount rates. For a public works project, any costs passed on to residents in the form of utility rates or taxes are determined according to the municipality's explicit financial calculations. In this situation, the decision-maker (the utility) explicitly chooses an appropriate market discount rate for the debt incurred by the project; the homeowner does not participate in this financial decision, so his/her discount rate is not relevant.

However, when homeowners decide to purchase or reject in-home technologies such as eco-toilets (flush diversion, dry diversion, and composting toilets, collectively), their decisions are based on a variety of homeowner and household conditions, such as access to capital, cash flow, expected time to selling the property, uncertainty about technology performance, etc.[16,24,33] Previous research suggests that such factors influence the individual discount rate that homeowners apply explicitly or implicitly to household financial decisions.[16,24,33]

Because public utilities and homeowners make separate and different calculations of the life cycle costs, three possible results in comparing these calculations can occur:

a) Both parties agree that one choice is the least expensive,

b) The utility finds the centralized option to be cheaper but the homeowner disagrees, or

c) The utility finds the decentralized option to be cheaper but the homeowner disagrees.

For case (a), the decision is clear. For case (b), the utility can likely mandate the centralized choice, following widespread precedent for requiring connection to public sewers.[34–38] Case (c) is the one of most interest here. In that case, municipalities would have difficulty in mandating adoption of an in-home technology. Precedent for changes in building codes, except in instances of clear and immediate danger, typically allows grandfathering of existing technologies; forced changes to existing private homes are likely to provoke lengthy and costly legal and political battles. However, monetary incentives might persuade homeowners to install decentralized technologies and thus bypass the challenges of a mandate. Incentive programs are quite common for energy-saving technologies, with some U.S. states offering over 100 different rebate, tax credit, loan, and other incentive-type programs,[39] providing ample examples for how incentive programs might be conducted.

The two key questions that must be answered before monetary incentives are offered are:

1. will the incentive be large enough to persuade homeowners to install the decentralized technology?

2. will the incentive payouts make the decentralized option more expensive, in total, than the centralized one?

The answers to these questions hinge on the value of the individual discount rate.

Case Studies

The analysis addresses the research questions for a comparison of six systems, initially chosen for applicability in previous research[8] and used here for comparison between studies. These systems all manage greywater, feces, and urine, some with a single technology and others with a combination of complementary technologies:

1. Centralized wastewater treatment plant with sewer collection network (collectively referred to herein as WWTP);

2. Innovative or advanced septic system serving a single home (I/A septic);

3. Flush urine-diversion toilets, with urine collected in a dedicated tank for separate disposal, paired with a conventional septic system for greywater and feces management (flush diversion – first case study only);

4. Dry (composting) urine-diversion toilets, with urine collected in a dedicated tank for separate disposal, paired with a conventional septic system (first case study) or a connection to a sewer (second case study) for greywater management (dry diversion);

5. Composting toilets paired with a conventional septic system (first case study) or a connection to a sewer (second case study) for greywater management (composting);

6. Anaerobic blackwater digestion plant with pressure or vacuum sewer collection network serving a cluster of homes or a neighborhood, paired with a conventional septic system (first case study) or a connection to a sewer (second case study) for greywater management (digester).

Two specific case studies are analyzed to illustrate both the execution of the method and the range of possible results. Both cases share the critical characteristic that two separate decision-makers (the utility and the homeowner) participate in the choice of which sanitation technology to implement.

The first case is Falmouth, Massachusetts, a town of approximately 32,000 people on Cape Cod.[2] Many bays and waters around Cape Cod have been suffering from excessive nitrogen loading and ensuing eutrophication. Seepage from septic systems is a major driver of this pollution, with approximately 95% of Falmouth homes using conventional septic systems to manage wastewater.[40,41] Cape Cod's municipalities are considering a wide range of possible solutions to mitigate the pollution, many of which rely on improved household sanitation systems, including the systems considered here. Because of the existing infrastructure of septic systems in this case, systems three through six in the above list include conventional septic and not centralized treatment in the combination of complementary technologies.

In the second case, the Allegheny County (Pennsylvania) Sanitary Authority (ALCOSAN) already has a centralized WWTP system serving the 350,000 households, but CSOs are driving costly system upgrades to reduce pollution of receiving waters during wet weather events; these upgrades are detailed in ALCOSAN's Wet Weather Plan (WWP).[42] Because "fecal coliform is the primary pollutant of concern,"[42] this study proposes that managing household human waste with a decentralized technology (and thereby removing it from the municipal wastewater stream) might be less expensive than treatment plant upgrades to attain the required water quality goals. That is, human fecal matter and (in most cases) urine would be treated on-site at each household while all other domestic wastewater would go directly to the existing sewer and centralized treatment facility. Thus the alternatives are (a) moving forward with the proposed upgrades, or (b) installing decentralized technologies in homes alongside the existing sewer and treatment system without completing the upgrades. Because of the existing sewer collection system in this case, systems four through six in the above list include the centralized treatment and not conventional septic in the combination of complementary technologies. System three (flush diversion) is excluded from this case study because it does not remove feces from the wastewater stream and thus will not reduce fecal coliform pollution in CSOs.

METHOD

No implicit discount rates for household decisions on sanitation technologies have been reported; however, ample data on such values for energy-efficient technology purchases are available. Using life cycle cost data for both centralized and decentralized systems, threshold discount rates (*i.e.*, those that define boundaries between regions of expected outcomes) can be calculated for sanitation technologies and then compared to the literature values for energy efficiency. These values for energy-efficient purchase decisions serve as guides for interpreting the boundaries and regions of expected outcomes for sanitation-related projects. Therefore, this study uses a threshold approach to answer the two key questions, above, that must be answered before monetary incentives are offered.

The threshold analysis determines the *breakeven point*: the (implicit) individual discount rate that defines the boundary between regions of expected outcomes for decisions about adopting decentralized sanitation technologies. The premise of the analysis is that the decision is based entirely on financial criteria, assuming that the discount rate incorporates other consumer preferences into the financial analysis, as discussed previously. The breakeven point is defined by the comparison of net present value (NPV) of the centralized and decentralized systems calculated from the homeowner's perspective, because the homeowner is the party that decides based on this comparison.

The homeowner will consider the alternatives – centralized and decentralized systems – and choose the one with the smaller NPV of costs, according to his/her own (explicit and/or implicit) cost calculations. The cost difference dictates his/her decision; if the municipality offers him/her a financial incentive that makes the two alternatives equal in cost (from his/her perspective), the homeowner will be indifferent between the two. The cost difference between systems is the dollar amount that makes the homeowner indifferent; this amount is the minimum incentive that will be acceptable to the homeowner and persuade him/her to choose the decentralized alternative.

On the other hand, the utility can calculate a maximum amount for the incentive based on its calculations of the NPV of the alternatives. That amount would be the difference between the NPVs because such an incentive would make the municipality indifferent between the two alternatives. Any higher incentive would make the centralized choice the cheaper alternative, and therefore it would not be worthwhile to pay such an incentive. Even though all funds might ultimately come from homeowners, via fees or taxes, we assume the municipality considers the total cost in its decision to reflect the public's best interest.

The breakeven point occurs when the minimum incentive that will persuade the homeowner to accept the decentralized system equals the maximum amount that the municipality is willing to offer as incentive. This breakeven point defines the boundary between conditions under which incentives are likely to succeed and conditions under which they are likely to fail. If the individual discount rate is above the breakeven point, an incentive program will fail: this higher discount rate means homeowners will weight up-front costs more heavily and benefits over time less heavily, driving the needed incentive amount up if the incentive is paid over time. Thus when the individual discount rate is above the breakeven point, the maximum incentive the municipality is willing to offer is smaller than the minimum needed to persuade the homeowner: the homeowner will not agree to install the decentralized system. If the individual discount rate is below the breakeven point, the situation is reversed and the homeowner will be persuaded by an incentive equal to or smaller than the amount the municipality is willing to offer; agreement will be reached to adopt the decentralized system. The breakeven point is calculated by allowing the individual discount rate to vary, since all other values used to calculate NPV from both perspectives are set according to cost and other data.

In this analysis, variability and uncertainty were explored using several scenarios and situations.

- Life cycle cost estimates for both case studies include ranges of cost estimates for all parameters. In analysis of breakeven points, cost scenarios examine all nine possible combinations of low/base/high cost estimates for both the centralized and decentralized systems.

- In both case studies and all cost scenarios, the incentives offered by the municipality are distributed into three possible cash flows: one with the entire incentive paid up front, one with annual incentive payments spread equally over time, and one with half the incentive paid up front and half spread over time in annual payments.

- For the Falmouth case, two possible cash flows were considered for the WWTP-related costs imposed on homeowners. The centralized system costs are based on an actual impending project for which the town will assess betterment fees as property liens, anticipated to be approximately $18,000 per equivalent unit. These fees will be paid in equal payments over 30 years at an interest rate of either 0% or 2%, depending on the town's ability to secure a 0% State Revolving Fund loan;[43] two cash flows, reflecting these two interest rates, are considered.

- In the ALCOSAN case, only one cash flow was considered for the centralized system upgrades, because the only option presented in the WWP documentation is a rate increase.[42]

- For both cases and all of the above scenarios and cash flow situations, the analysis was repeated for retrofits of existing homes and for new home construction, with differences including removal of existing toilets and potential rehabilitation or replacement of failing existing septic systems (in the Falmouth case).

The method used to calculate this breakeven point is enumerated in Equations 1 – 8, which explicate the comparison between the minimum incentive the homeowner is willing to accept and the maximum incentive the municipality is willing to offer. All variable names are defined below and, except for the individual discount rate, all values in these equations are known or are assumed based on predefined cost scenarios and cash flows.

In Equations 1 and 2, the NPV for each system is calculated from each party's perspective. Both equations allow for the possibility that some or all of the up-front cost for any system could be financed with a loan and paid off over time; this possibility was exercised by examining scenarios in which the homeowner pays immediately for all, half, or none of the up-front cost of a decentralized system and finances the remaining costs, but inclusion of the parameters z (the fraction of the up-front costs that is financed through a loan), t_{HH} (the term of the homeowner's loan), and i_{loan} allows flexibility in determining cost and financing scenarios. The parameter i_{loan} refers to the real loan rate for any personal loan taken by the homeowner to cover up-front costs; here, it was constrained to equal the municipal discount rate because both are based on prevailing market interest rates, but such matching is not necessary. The fraction of up-front costs financed through a homeowner's loan (z) corresponds to the cost scenario for the system and thus is not constrained to be equal in calculations from the municipality's perspective and those from the homeowner's perspective.

Eq. 1) $$NPV_{mun} = \sum_{up-front\ components}\left[q(1-z)c + qzc(AF(t_{HH}, i_{loan}))(PVF(L \times 12, {}^{i_{mun}}/_{12})\right] + \sum_{all\ annual\ components}\left[qc\left(PVF(L, i_{mun})\right)\right]$$

Eq. 2) $$NPV_{HH} = \sum_{up-front\ components}\left[q(1-z)c + qzc(AF(t_{HH}, i_{loan}))(PVF(L \times 12, {}^{i_{HH}}/_{12})\right] + \sum_{all\ annual\ components}\left[qc\left(PVF(L, i_{HH})\right)\right]$$

Where:

- NPV is net present value,
- q is number of components included in the installation (*e.g.*, one household might install two toilets),
- z is the fraction of the up-front costs (capital and installation) that is financed through a loan,
- c is the cost per component,
- t_{HH} is the term of the homeowner's loan in years,
- L is the financing period of time over which annual incentives are offered and over which all options are evaluated,
- i is an interest or discount rate,
- subscript "loan" is the interest rate of the loan,
- subscript "mun" refers to the municipality's perspective or the discount rate used by the municipality for public works,
- subscript "HH" refers to the household discount rate or the homeowner's perspective,
- AF is an annuity factor with terms specified in parentheses,
- PVF is a present-value factor with terms specified in parentheses,
- and monthly compounding of loan interest is assumed.

Equations 3 and 4 reflect each party weighing the costs of the two systems and finding how much money is needed to make the two costs equal. Note that the homeowner only demands an incentive if the decentralized system is more expensive than the centralized system, from his/her perspective. Likewise, the utility will only offer incentives if the centralized system is more expensive than the decentralized system. Therefore, these equations reflect that the differences are greater than zero in the scenarios of interest.

Eq. 3) $maximum\ incentive\ offered = NPV_{mun,C} - NPV_{mun,D}$

Eq. 4) $minimum\ incentive\ accepted = NPV_{HH,D} - NPV_{HH,C}$

Where:

- subscript "D" refers to the decentralized system,
- subscript "C" refers to the centralized system,

In Equations 5 and 6, the maximum incentive that the municipality is willing to offer (from Equation 3), is first allocated into a cash flow and then converted to a net present value from the homeowner's perspective. As written, these equations illustrate the incentive cash flow option #2: the entire incentive divided into equal annual payments; the other two cash flow options (cash flows #1 and #3) are illustrated in Appendix B. Regardless of cash flow, the method is the same.

Eq. 5) $incentive\ cash\ flow\ \#2 = (maximum\ incentive\ offered)\big(AF(L, i_{mun})\big)$

Eq. 6) $NPV\ of\ incentive\ cash\ flow\ \#2_{HH} = (incentive\ cash\ flow\ \#2)\big(PVF(L, i_{HH})\big)$

Equation 7 states in mathematical terms the comparison between the maximum incentive offered and the minimum incentive accepted, from the homeowner's perspective, where = = indicates a comparison rather than an equality:

Eq. 7) $NPV\ of\ incentive\ cash\ flow\ \#2_{HH} == minimum\ incentive\ accepted$

or, with appropriate substitutions:

Eq. 8) $\big(NPV_{mun,C} - NPV_{mun,D}\big)\big(AF(L, i_{mun})\big)\big(PVF(L, i_{HH})\big) == NPV_{HH,D} - NPV_{HH,C}$

where the only unknown is the homeowner's individual discount rate i_{HH}, which is solved for. The breakeven point is the specific value of the variable i_{HH} that causes the left and right sides of this comparison to be equal. All other values are set according to collected data and necessary assumptions.

Besides calculating the breakeven point, the model identifies the scenarios in which (a) the municipality chooses the centralized system and thus has no reason to offer incentives for the decentralized system and (b) the homeowner chooses the decentralized system without requiring incentives, up to some threshold individual discount rate at which he/she begins to demand incentives. Note that this value is distinct from the breakeven point, which is the threshold above which incentives will not convince him/her to implement a decentralized system.

Data for the Falmouth case study can be found in Wood *et al.*,[8] and data for the ALCOSAN case study can be found in Appendix B. In all instances, the real system cost includes the cost of debt service, whether personal or institutional debt. Assumptions include no salvage value for any technology, no cost increases over time, no economic deterioration over time, no differential expected inflation rates of purchase price and electricity price, and no monetary benefit from sale of potentially usable waste products. For more detail on the life cycle cost estimates, see Appendix B.

RESULTS AND DISCUSSION

Breakeven points were found for the scenarios detailed above: nine cost scenarios and three possible cash flows for incentive payments (27 iterations) for both case studies, with the same iterations repeated for both possible centralized system cash flows for Falmouth. The entire analysis was completed for both retrofits of existing homes and new home construction. Figure 4.1 illustrates results for retrofits of existing homes for the five decentralized systems for Falmouth (Part A) and the four decentralized systems for the ALCOSAN area (Part B). This figure reflects only one of the possible cash flows for incentive payments: that in which the incentive dollars are spread into equal annual payments. Spreading the incentive over time is a conservative assumption: that is, this cash flow makes the breakeven point most likely to be under 1,000% because the alternative assumption (paying half or all of the incentive up front) increases the homeowner's propensity to accept the incentive. For Falmouth, the betterment interest of 0% is shown. Results for other cash flows and for new home construction follow the same patterns as the results shown here; additional results are in Appendix B.

In addition to breakeven points that delineate the regions in which incentives are and are not likely to succeed, Figure 4.1 shows other possible outcomes of the two-party decision process. Several system/cost-scenario pairs are marked as "Choose C," meaning that the municipality chooses the centralized system. In these instances, calculations from the municipality's perspective show that the centralized system is less costly than the decentralized system, even without incentives. As explained previously, the municipality can require homeowners to participate in the centralized system in these instances. Recall that the centralized option in the ALCOSAN case (Figure 4.1B) does not comprise a newly constructed sewer system and treatment plant, but only upgrades to the existing system.

The remaining system/cost-scenario pairs show ranges of individual discount rates where homeowners choose decentralized systems without needing incentives and where incentives are both necessary and viable. The lower range of individual discount rates (solid black in the figure) is where the homeowner will choose the decentralized system without requiring incentives. For some scenarios (arrows in the figure), this range extends to at least 1,000%, the maximum realistic value of real individual discount rates in homeowner decisions, according to previous literature.[19,24,25,28,29] So, for these scenarios, the municipality and the homeowner will agree to implement the decentralized system, and no incentive is needed.

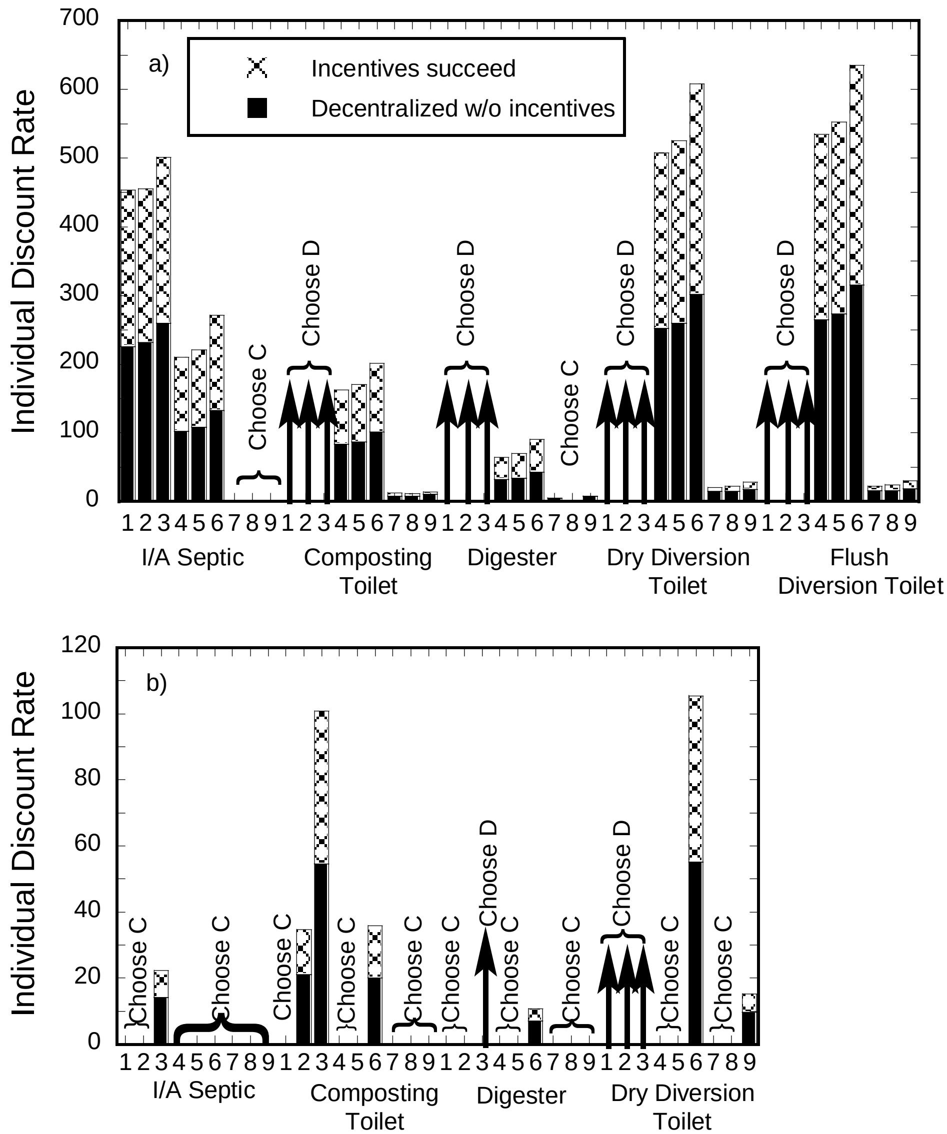

Figure 4.1. Breakeven points for (a) Falmouth case study and (b) ALCOSAN case study, retrofits of existing homes

Notes: D is decentralized system, C is centralized system. The cost scenarios are denoted by the numerals 1-9: (1) D low cost, C low cost; (2) D low cost, C base cost; (3) D low cost, C high cost; (4) D base cost, C low cost; (5) D base cost, C base cost; (6) D base cost, C high cost; (7) D high cost, C low cost; (8) D high cost, C base cost; (9) D high cost, C high cost. For (a) Falmouth case study, C cash flow assumes 0% interest for betterment payments. For both cases, incentive payment cash flow assumes incentives spread out over time in equal annual payments.

For most scenarios shown, a range of individual discount rates will lead homeowners to choose the decentralized system without any incentive. At higher values of the individual discount rate is the critical range (shown with cross-hatch bars) under which incentives are required to convince the homeowner to implement the decentralized system *and* those incentives are deemed worthwhile by the municipality. This range of individual discount rates is where incentives are both necessary and likely to succeed at bringing both parties into agreement to implement the decentralized system. The top of this range is the breakeven point. If the individual discount rate is above this range, the municipality deems the incentives too expensive and chooses to implement the centralized system instead of incentivizing the decentralized system.

Comparing Systems, Cost Scenarios, and Case Studies

One conclusion from Figure 4.1 is that, based on the cost estimate ranges in the data for these two cases, the variation in the cost of the centralized option has less effect on the individual discount rate thresholds than does the variation in the cost of the decentralized options, with this pattern holding more strongly in the Falmouth case than the ALCOSAN case. Given the potential cost savings and expected investment in discovery, this result suggests that refining cost estimates for decentralized systems is a better investment of resources than refining cost estimates of centralized options. Further, in the Falmouth case, if true individual discount rates are 100% or less, all decentralized systems are viable options if the system costs equal the low scenario estimates, and most decentralized systems are viable if the costs equal the base ("most likely") estimates. For ALCOSAN, decentralized systems are highly unlikely to be viable alternatives to the WWP upgrades, regardless of true individual discount rate, unless the decentralized system costs equal the low scenario estimates. In particular, the I/A septic system results shown assume that the homeowner would not pay any centralized wastewater costs, due to using the I/A septic system for all household wastewater, but if the homeowner were required to contribute to the upkeep of the centralized system, the I/A septic system is an even less likely candidate.

In both case studies, diversion toilets appear most likely to be viable under the largest number of cost scenarios. The patterns seen across the cost scenarios depend on the division of costs between up-front and annual expenses. See Appendix B for further discussion.

The Falmouth case shows greater likelihood of decentralized systems being adopted, with or without incentives, than the ALCOSAN case. This difference is caused by the differences between the centralized options: in Falmouth, an entirely new sewer system and treatment plant are proposed, whereas for ALCOSAN, the centralized option comprises upgrades to an existing system, with expenses shared among 350,000 households. These insights highlight geographic variability in the need for and viability of incentives. In addition, true individual discount rates might vary between populations in the different locations.

Comparison with Discount Rates in Literature

Literature shows that true individual discount rates depend on factors such as income, decision-maker's age, amount of money in question, and information presented to the consumer at the time of purchase; discount rates also seem to differ for gains and losses.[21,24,27,28] Discount rates for purchases of energy-efficient appliances range from approximately 0%[24] to over 800%;[25] most available data fall between 10% and 100%, though multiple authors present rates well over 100%.[19,24,25,28,29] Some authors[20,21,24] examined real purchase data (as opposed to responses to questions about hypothetical costs and benefits) on investments in major appliances (air conditioners) or home improvements (rooftop photovoltaic and thermal shell improvements), and they present results according to household income. Referencing the median incomes in Falmouth and the ALCOSAN area of approximately $39,500 and $30,500, respectively,[2] and averaging the literature results from these three real purchase data studies results in estimated median individual discount rates in Falmouth and the ALCOSAN area of 28% and 37%, respectively.

If these median individual discount rates are indeed representative for the study areas, the breakeven points can be interpreted to show expected outcomes. For Falmouth, the 28%

individual discount rate would mean that homeowners will agree to install any of the decentralized systems without incentives if the low or base cost estimates are appropriate for the decentralized system, regardless of which cost estimate applies for the centralized system. If the high costs apply for decentralized systems, expected outcomes vary: the I/A septic system will be rejected by the municipality in favor of the centralized system regardless of which centralized cost estimate applies, incentives might successfully bring the municipality and the homeowner into agreement to adopt the flush diversion or dry diversion toilet if the high cost estimate applies for the centralized system, and incentives will fail to bring the municipality and the homeowner into agreement for all other cost scenario/system pairs.

For ALCOSAN, outcomes for most cost scenario/system pairs do not vary with the individual discount rate (in the chosen range of 0% to 1000%). For the remaining pairs, an individual discount rate of 37% would mean that homeowners will agree, without incentives, to install the composting toilet (for low decentralized cost estimate and high centralized cost estimate), or the dry diversion toilet (for base decentralized cost estimate and high centralized cost estimate). For that discount rate, no cost scenario/system pair shows incentives being necessary and succeeding at bringing the parties into agreement. As Figure 4.1B shows, for several cost scenario/system pairs, the digester and dry diversion toilet will be adopted by the homeowner with no incentives for any individual discount rate up to 1,000%. Therefore, if this literature-based value of 37% is accurate for the median individual in this case, ALCOSAN has no financial reason to offer incentives for decentralized technologies.

Key Findings and Opportunities for Further Research

The results of this study can help municipal decision-makers evaluate plans for monetary incentive programs for decentralized sanitation systems, and the concepts and methods herein apply to any technology adoption decision process in which two different decision-makers must reach agreement in spite of different discount rates. Given the breakeven points calculated here, decentralized options can satisfy both decision-makers in the Falmouth case (with incentives in some cases), while the ALCOSAN utility is less likely to find an acceptable decentralized alternative to the planned CSO upgrades. However, individuals with incomes lower than the median are expected to have higher individual discount rates;[21,24,28] therefore, municipalities should expect some homeowners not to be persuaded to adopt decentralized sanitation, even by the largest incentives municipalities are willing to offer. For in-home energy technologies, each homeowner decides independently of his/her neighbor, but for sanitation systems, every home in the area has to accept the same technology (or accept decentralized technologies, even if individual homes can choose different decentralized systems). Thus a municipality might consider the 75th or 90th percentile individual discount rate rather than the median to capture the preferences of a larger portion of the population.

Individual discount rates also can differ for different products and in different decision contexts.[18] If individual discount rates are a proxy for consumer preferences in purchase decisions, rates for sanitation technologies might be higher than those for energy-efficient technologies. Eliciting stated or revealed discount rates for decentralized sanitation technologies would allow better estimates of thresholds and improve decision-making.

Other factors influence both municipality and homeowner decisions. Municipalities might choose to pay incentives beyond the "maximum willing to offer" amount calculated here, because decentralized sanitation might accomplish desired environmental goals, for example. For the consumer, purchase decisions are based on product attributes as well as cost, so if various sanitation options are not deemed to provide equivalent services, discount rates might not correctly predict purchase choices (or different discount rates would apply to different technologies). This study assumes that the discount rate is an adequate proxy for non-monetary factors influencing the decision process, but explicit consideration of other factors might be critical, especially given social science literature examining the various social and psychological factors that affect individual and household decision processes; "although monetary incentives certainly have a calculable effect on monetary cost-benefit ratios, their impact on decisions are more contingent."[16] If the consumer purchase model were eschewed entirely in favor of the utility purchasing the decentralized systems and leasing them to homeowners, the financial hurdles might be overcome, though such a proposition would require extensive examination before being declared viable.

Finally, even if individual discount rates are high enough to hinder incentive programs, sharing information with the consumer might reduce discount rates and improve the success of such a program. Min *et al.*[28] found that providing information about estimated annual operation costs of energy efficient lightbulbs substantially lowered the average implicit discount rate from 560% to 100%. Further research on consumer education efforts might suggest strategies to complement monetary incentive programs and reach higher adoption rates by lowering individual discount rates.

Acknowledging the perspectives of the homeowner – the ultimate consumer of the decentralized technology – is critical in achieving solutions that manage household waste safely and effectively while promoting and sustaining healthy relationships between human communities and the natural environment. No matter how technologically promising a system might be, it cannot achieve either sanitation or sustainability goals unless people are willing to use it.

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Chapter 5: Adoption of Eco-Toilets by U.S. Homeowners: *A Case Study on Cape Cod*[4]

INTRODUCTION

Eco-toilets, an umbrella term used for composting toilets and urine-diversion toilets, are considered "ecological sanitation" technologies: options that address or avoid environmental problems associated with some conventional household sanitation systems. For example, eco-toilets allow for easy waste-to-resource recycling and reduce water usage compared to standard flush toilets. However, in a situation on Cape Cod in which eco-toilets could help mitigate an existing pollution problem, local residents have been reluctant to adopt these technologies even with incentives. Two preceding analyses showed that eco-toilets are expected to be the preferred option for Cape Cod according to cost and cost-effectiveness criteria, even when the complications of homeowners' individual decision-making are considered;[1,2] therefore, this study examines non-monetary factors affecting homeowners' willingness or reluctance to adopt eco-toilets in their own homes. Specifically, this study uses a household survey to examine two research questions:

1. Are U.S. homeowners in locations with wastewater management problems willing to install eco-toilets in their own homes?
2. Can any patterns be discerned in how willingness to install relates to relevant attitudes and perceptions or to demographic characteristics?

BACKGROUND

Cape Cod, Massachusetts, has a nitrogen pollution problem that experts attribute largely to conventional septic systems, which approximately 97% of Cape Cod land parcels use for wastewater management.[3] Local communities are considering a variety of possible solutions to reduce the flow of nitrogen into the sensitive coastal environment, including a range of new household sanitation technologies.[3] Wood and colleagues[1,2] completed a life cycle cost

[4] Research conceived by Wood and chapter written by Wood. Chapter edited by Lawler. Lawler and Blackhurst participated significantly in questionnaire design. Structural equation modeling guided by Musick.

comparison of a range of such technologies, examined the cost-effectiveness of proposed systems' ability to reduce the amount of nitrogen released into the environment, and extended the cost analysis to incorporate the homeowner as a second decision-maker in the technology adoption decision for decentralized sanitation systems. This previous work has indicated that an eco-toilet technology is a preferred option for Cape Cod to effectively mitigate nitrogen pollution at lower cost than other options. However, where monetary incentives have been offered in the town of Falmouth, out of approximately 20,000 homes in the town, reportedly only 10 households have taken the incentive and installed eco-toilets; one homeowner in another Cape Cod town installed eco-toilets without any incentive; and one further homeowner has expressed interest for three years without actually installing eco-toilets.[4] This minimal adoption rate attests to the gap between the expectation based on cost and cost-effectiveness criteria and the reality of homeowners' decisions to install eco-toilets in their homes.

Adoption of decentralized technologies depends on individuals' decisions on more dimensions than simply the financial. Over approximately the last two decades, only minimal research has investigated various aspects of acceptance of eco-toilets by users, and no existing literature addresses situations like those found on Cape Cod. Several studies have investigated the acceptance of composting toilets already installed in homes in developing countries,[5–8] where sanitation systems do not yet exist or do not serve large portions of the population; these studies frequently compare eco-toilets to the alternatives of latrines or open defecation, which are not appropriate alternatives in the Cape Cod case. The Novaquatis project undertaken by EAWAG (Swiss Federal Institute of Aquatic Science and Technology) from 2000 to 2006 extensively researched various aspects of urine-diversion toilets, including perceptions and attitudes, but only in European countries, mostly in Switzerland, and almost exclusively in public places.[9] One Novaquatis paper mentions a pilot project in which urine-diversion toilets were installed in four apartments in a single building per the building management's decision to create eco-friendly housing; however, four families is an extremely small sample, no data are presented beyond a brief description of pilot project outcomes, and the researchers specifically cite "the perhaps most important gap" in their research as "lack of quantitative household studies."[10] In addition, all of the Novaquatis studies on perceptions surveyed people who had already used a urine-diversion toilet at least once, and who were presented with information on the toilets and their benefits; the homeowners in the small pilot study were already using the toilets in their homes, not facing the decision of whether to install them.

While understanding user experience is important for developing and modifying products to better suit consumers, proponents of eco-toilets must also understand non-users', *i.e.*, *potential* users' – perceptions of the technologies. Understanding both is necessary to combat the negative attitudes and beliefs that discourage adoption of these toilets and to encourage positive perceptions that might increase adoption. Such literature on surveyed perceptions of potential users exists in the context of conventional sanitation technologies, especially with regard to adopting sanitation in developing countries,[11,12] but not for eco-toilets. Surveys that examine the perceptions of non-users have been reported for other technologies, such as the recycling and reuse of wastewater for potable and non-potable purposes. Haddad, Rozin, Nemeroff, and Slovic[13] and Ogilvie, Ogilvie & Company[14] both consider the psychology behind individuals' perceptions of treating wastewater for reuse, especially the attitudes that might be considered "irrational" from an economic or engineering perspective: these attitudes include the "yuck factor" that refers to feelings ranging from disgust (relevant in the water reuse context) to moral outrage (relevant to contexts such as human cloning).[14] While such studies suggest factors that might influence individual decision-making on a related issue such as sanitation technology, they do not directly uncover homeowners' perceptions of technologies that will change their daily interactions with their sanitation systems.

The survey research discussed herein, specific to Cape Cod, begins to fill a critical gap in the existing literature. Because fecophobia and fecophilia vary among cultures,[15,16] it is important to consider a U.S. case study; it is possible that different regions of the U.S. also will vary in their tolerance for sewage management moving closer to home, and it is very likely that the U.S. differs from Europe in this respect, given other known cultural differences.[17–19] In addition, residents on Cape Cod are in the unique position of not yet having eco-toilets in their homes but facing the real possibility that they will be required to install them in the near future, unlike the studies focusing on eco-toilets already installed or the Novaquatis surveys in which existing natural monopolies in local wastewater systems make the possibility of installing an eco-toilet in one's home entirely hypothetical.[9,20] Finally, the studies most similar to this survey of Cape Cod residents – the Novaquatis studies – showed that respondents tended to be environmentally minded, and that certain demographic factors such as age and "mood" increased willingness to accept eco-toilets;[21] across Cape Cod, such factors vary across the population and they cannot be changed easily or at all. The questionnaire developed and implemented in this research helps to illuminate the realistic possibility of adoption of eco-toilets by the existing population on Cape Cod, not by a hypothetical population or one predisposed to prefer an ecologically friendly sanitation technology.

METHODS

Model and Item Development

The underlying theoretical model and questionnaire items for this household survey were developed based on existing literature, data collected in semi-structured interviews, expert review, and pilot testing. The theoretical model consists of constructs and variables, some of which are expected to be predictors of others. Endogenous constructs are similar to dependent variables in a regression model; more strictly, they are determined by other model constructs. Exogenous constructs are similar to independent variables in a regression model; they are not determined by other constructs in the model. The distinctions "endogenous" and "exogenous" allow for more complex relationships between constructs than "dependent" and "independent." Data are collected using the questionnaire to allow for testing of the relationships among the constructs in the model.

The theoretical model is based on that developed by Hines *et al.*[22] from their meta-analysis of environmental behavior. That model includes the constructs of action skills, knowledge of action strategies, knowledge of issues, attitudes, locus of control, and personal responsibility as exogenous predictors of the endogenous construct intention to act. The current study adds to that model the exogenous constructs of social and personal norms as well as demographic information. Our model also terminates at intention to act, rather than at Hines *et al.*'s endpoint of responsible environmental behavior, because intent or willingness to act (adopt eco-toilets) is of current interest in the Cape Cod situation, rather than action itself.

The portion of the model based on Hines *et al.*[22] encompasses only the latent constructs of interest, which cannot be directly observed. A measurement model was created to associate indicators, or observed variables, with these latent variables. Figure 5.1 shows the full model, with observed variables in rectangles and unobserved variables in ovals. Directional relationships are shown with arrows in the figure, with the direction indicating that the variable the arrow is pointed from is expected to affect the variable the arrow is pointed toward.

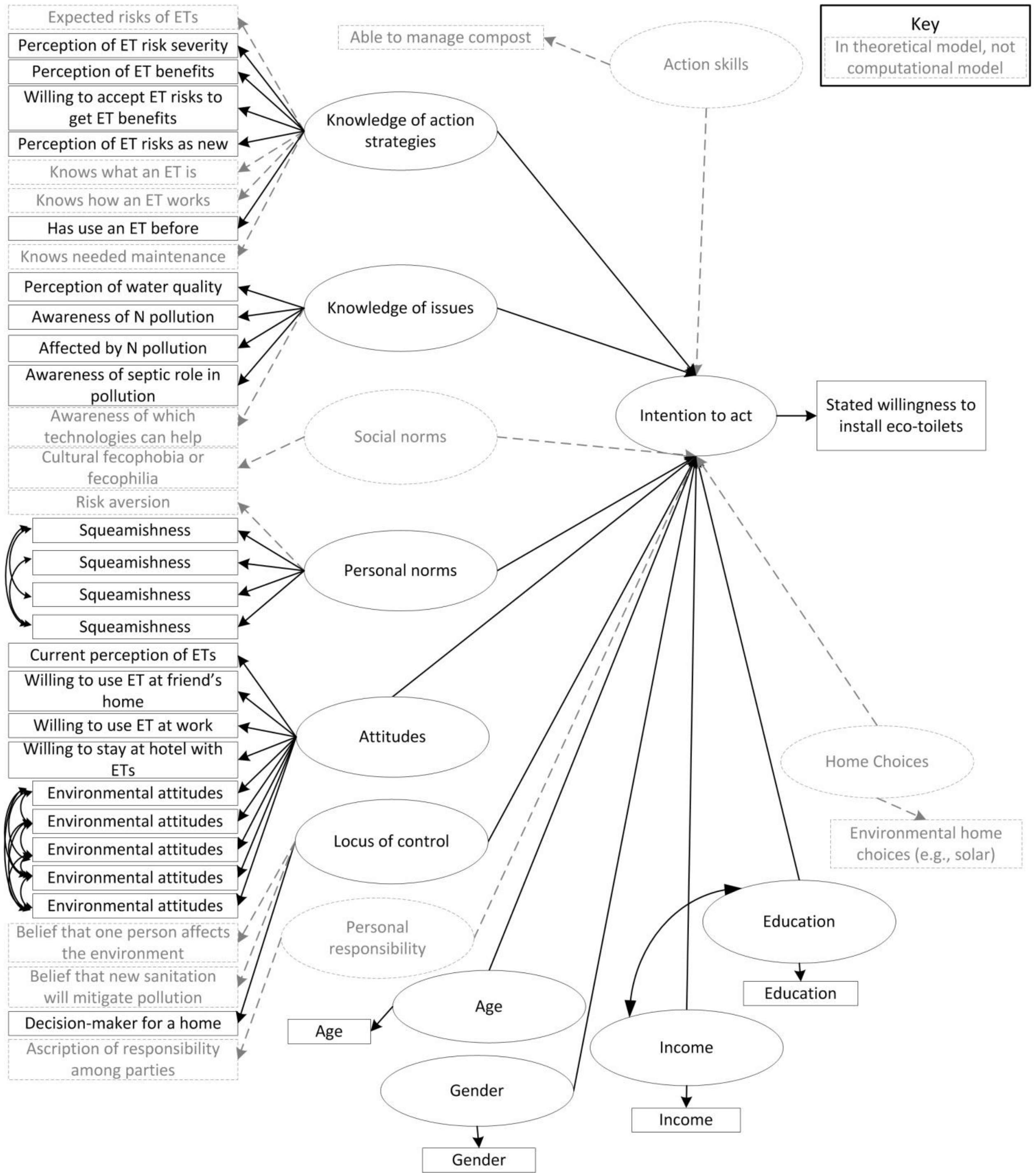

Figure 5.1. Theoretical model of factors influencing willingness to install eco-toilets.
Notes: Latent constructs (unobserved variables) are in ovals and indicators (observed variables) are in rectangles. ET is eco-toilet.

Indicators are directly reflected by items in the questionnaire whenever possible: the variables in Figure 5.1 shown in rectangles in solid black print correspond to individual questionnaire items. Some indicators could not be queried due to various constraints. For example, questions testing homeowners' knowledge about eco-toilets were omitted to reduce the risk of alienating respondents by asking questions they might not feel able to answer. The length of the questionnaire was also limited to increase response rate. Survey items were taken directly from established measures when possible or created specifically for this questionnaire based on responses given in interviews (discussed below), expert input, and feedback from pilot study participants.

Indicators for knowledge of action strategies focus on the risks and benefits of using eco-toilets and on questions homeowners have about eco-toilets. The risk and benefit questionnaire items were adapted from Slovic *et al.*'s[23] original presentation of similar items and Savadori *et al.*'s revision of these items.[24] Slovic *et al.* explored experts' and lay peoples' perceptions of and attitudes toward risk; they presented 18 risk characteristics, or dimensions, that can be evaluated for various scenarios to measure risk perception. Savadori *et al.* applied 16 of these dimensions to further exploration of risk perception and revised some of the items and response scales to be clearer than they were in the original Slovic *et al.* paper. Items examining homeowners' questions about eco-toilets were based on semi-structured interviews, discussed subsequently.

Questionnaire items indicating knowledge of issues were taken from an existing unpublished survey of economic issues on Cape Cod, created and implemented by the Cape Cod Commission, and additional items were created based on input from experts on Cape Cod. These items examine perceptions of the local nitrogen pollution problem and the roles that various technologies might play in causing and mitigating the problem.

Indicators for personal norms focus on "sensitivity to disgust" as measured by items from the revised Disgust Sensitivity Scale, which was first published by Haidt, McCauley, and Rozin,[25] and revised by Olatunji *et al.*[26] The revised disgust scale includes 25 items to examine the separate constructs of "core disgust," "animal reminder disgust," and "contamination-based disgust," based on the authors' underlying theory of disgust.[26] The core and contamination-based disgust constructs are most relevant to this study as they refer to "a sense of offensiveness and the threat of disease" and "the perceived threat of transmission of contagion."[26] These two dimensions are measured by 17 of the 25 questions in the scale. For the sake of survey length, eight of these items were chosen that appear most relevant to this study: for example, "You are about to drink a glass of milk when you smell that it is spoiled" (scale from "not disgusting at all" to "extremely disgusting").[26] After initial pilot testing, the survey was revised to include only four questions from the revised disgust scale, choosing questions that were expected to elicit a range of responses.

Attitude indicators probe perceptions of eco-toilets specifically as well as more general environmental attitudes. Environmental attitudes were explored with items from the New Ecological Paradigm Scale (NEP),[27] which is a revision of the original New Environmental Paradigm Scale.[28] The NEP is designed to "tap 'primitive beliefs' about the nature of the earth and humanity's relationship with it."[27] Specifically, the items in the survey address five aspects of environmental attitudes: "the reality of limits to growth, antianthropocentrism, the fragility of nature's balance, rejection of exemptionalism, and the possibility of an ecocrisis."[27] However, the authors' testing of the revised scale showed that all items appear to measure a single construct;[27] therefore, questions were chosen covering all five facets to capture the breadth of the scale.

The demographic section of the questionnaire includes standard demographic items as well as questions specific to the subject matter, such as what type of wastewater system is currently installed on the respondent's property and whether the respondent has participated in any workshops or meetings about the Cape Cod wastewater problem. Demographic questions were taken from the U.S. Energy Information Administration's 2009 Residential Energy Consumption Survey whenever possible.[29]

To supplement the literature review during the development of the survey instrument, semi-structured interviews were conducted via telephone with five individuals. The interviewees were all white American adults who own homes, four female and one male, with ages in their twenties, thirties, forties, and sixties. All participants had bachelor's degrees or higher and two had backgrounds in environmental and water resources engineering. Income was not queried. In many ways this pool is similar to the population of Cape Cod, which is overwhelmingly white (92.7%), about half female (52.4%), mostly aged 18-65 (57.7%), and largely college-educated (39.9% bachelor's degree or higher).[30] The pool of interviewees is clearly more heavily weighted toward women and somewhat more highly educated than the population of Cape Cod. The participants also were not from Cape Cod, though three were from the Northeast U.S. The respondents who have studied environmental and water resources engineering were included because that background makes them likely to be aware of eco-toilets and to have some general knowledge about their benefits, but unlikely to have detailed knowledge about them or personal experience using them (as confirmed in the interviews). This level of knowledge parallels what is likely to be found on Cape Cod based on the ongoing public conversation about water pollution and the possible role of eco-toilets in providing a solution, which is likely to raise awareness about the technologies and their stated benefits without providing detailed knowledge.

Interview questions probed knowledge of and perceptions about eco-toilets as well as related behaviors such as use of environmentally friendly technologies; responses followed patterns that contributed to the development of the theoretical model and questionnaire items. Respondents expressed a desire to gain knowledge about eco-toilets, focusing primarily on the advantages (non-monetary and monetary) and disadvantages of using the toilets. Concerns about the risks of using eco-toilets were frequently mentioned, and interest in benefits was prominent in most of the interviews. Respondents also discussed the importance of personal experience with the technology in making a decision about installing it in the home. Related behaviors were mentioned mostly in response to direct queries but were occasionally mentioned independently in conversation.

Questions about monetary decision factors were largely excluded from the questionnaire for the sake of length and because the preceding stages of research examined cost aspects of eco-toilet implementation. However, a few questions were included to allow for rough estimation of the individual discount rate for comparison with previous analysis that used the individual discount rate as a proxy for a homeowner's decision factors.

Findings from literature and interviews were incorporated through iterations of feedback and revision. Six pilot test participants completed the questionnaire and provided feedback from the respondent perspective. That feedback was incorporated and the questionnaire sent to experts in both sanitation technologies and survey design for content validity review. After this review, one additional round of pilot testing (five respondents) was carried out to ensure that item wording was clear and that time to complete was appropriate. Unfortunately, resource limitations precluded pilot testing on a large enough scale to provide sufficient data for construct validity testing. Various aspects related to construct validity were examined through the structural equation modeling discussed subsequently; complete construct validity testing should be completed after any additional revision of the questionnaire as part of future research. The final questionnaire can be found in Appendix C.

Data Collection

This survey was intended to study homeowners in Harwich, Massachusetts (demographically similar to Cape Cod as a whole) and the surrounding area. This population was chosen because of the current initiative on Cape Cod to improve wastewater management to reduce local water pollution; eco-toilets in particular are being considered as a possible solution in several places on Cape Cod, making it a particularly interesting population due to people's awareness of eco-toilets and the relevance of this study to their real situation. In addition, Harwich was recommended by various professionals familiar with the situation on Cape Cod as a town in which residents are likely to be responsive to a survey study. All adults in Harwich were eligible to take the survey; few, if any, participants were expected to have eco-toilets already installed in their homes since special permits are currently required for these technologies and since very few homeowners on Cape Cod have installed eco-toilets.[4]

Because of limited resources for implementation, the avenue chosen was to contact participants using the U.S. Postal Service's Every Door Direct Mail postcard delivery service. Invitations were sent to all postal customers in Harwich, West Harwich, and Harwichport, totaling 9,101 homes. Additional invitations were sent to surrounding communities via public libraries. This method of reaching out to potential respondents resulted in a sample of convenience, discussed further in the Limitations section.

A large number of participants was desired: at least 280, according to the rule of thumb that suggests the need for at least 10 respondents for every item within the perceptions domain of the questionnaire.[31] The total number of questionnaires received was 131, with 97 completed. Again, the Limitations section includes discussion of the sample.

A web survey was used for all data collection via the Qualtrics online questionnaire platform. This method was preferred for low cost of data collection, ease of participation, and ease and low cost of data entry (since data was entered directly by respondents). The web link was included on the invitation for participants to respond online. A link also was available for participants to download a PDF of the questionnaire if they preferred to complete a hard copy and mail it; no questionnaires were received through the mail.

Data Cleaning and Analysis

Data were collected via web survey, so data were entered directly by participants and digital files were simply downloaded when implementation was complete. Basic data cleaning was accomplished using Microsoft Excel to directly edit comma-separated-value data files. Variable names were assigned and unnecessary metadata were removed. Open-ended responses were stored intact for reference; they were not coded for quantitative analysis.

All further data processing was done using SAS 9.4 statistical analysis software. Responses were recoded as necessary to ensure that low and high scores on various items would align with comparable interpretations across variables (*e.g.*, a higher score always means a more favorable perceptions of eco-toilets); missing values were recoded with the missing data marker used in SAS. Simple summary statistics were reviewed to ensure that ranges and means for all data were as expected for each variable. Because no questions had responses related to each other in predictable ways (*e.g.*, no questions asked about parts that should sum to a total of 100%), no additional data cleaning such as ratio or balance edits was necessary. Summary statistics also were used as the basis for much of the interpretation of results. Inferential statistics were not appropriate because the data were collected from a sample of convenience.

In addition to summary statistics, structural equation modeling was used to compare the collected data to the theoretical model. Because data were not collected for all indicators in forms usable in structural equation modeling, a computational model was created to reflect only the indicators that could be included in the analysis (shown in Figure 5.1, above). In addition, a latent construct was added to the computational model for "missing on age or income," with indicators to flag records missing age data and records missing income data. Only these two variables were flagged for missing data because they had the largest percentage of missing values: 7% and 13%, respectively. Twelve other variables had 3% or fewer missing data points. Two different methods were used for imputing missing data: missing values were replaced with the variable's mean, or missing values were imputed using the expectation-maximization algorithm available in SAS that uses multiple imputation to create some variance in the imputed values. Structural equation modeling was completed in SAS using PROC CALIS with the LISMOD modeling language. Generalized least squares was used as the estimation method, and modification indices were generated.

Structural equation modeling compares the sample covariance matrix with the estimated population matrix, which is constructed from model parameters. The parameters are drawn from the theoretical model, including matrices of coefficients describing effects of variables on each other and matrices of variables' error variances. Modifying the model consists of creating or removing constraints on the matrices, such as requiring that a certain covariance be equal to zero or equal to another covariance value. Model modifications can also include removing indicator variables that do not contribute significantly to the model fit. To avoid infinite possible solutions for the estimated model parameter values, the model must be identified. The model used here is identified because the matrix of direct effects of endogenous latent constructs on each other (the B matrix, in structural equation modeling notation) and the covariance matrix of errors or disturbances on endogenous latent constructs (the Ψ matrix) are both diagonal matrices.[32,33] In addition, for each latent construct, one indicator's coefficient was set to a value of one to set the measurement scale; if the scale is not set in this way, an infinite number of parallel solutions are possible with values relating to different possible scales of the indicator values (*e.g.*, age could be in days, weeks, months, or years if the scale were left free).

The measurement model was analyzed first, using an iterative process to remove indicators not contributing to a well-fit model. For each iteration, the model was analyzed in SAS, the modification indices and the p-values of all coefficients were examined, and one modification to the model was then made from each iteration to the next. A critical p-value of 0.1 was used to guide this process, rather than 0.05, because the sample was small. This process was repeated until changes to the model no longer improved fit indices such as the adjusted goodness of fit index (AGFI) and the root mean square error of approximation (RMSEA).

After the measurement model had been revised, the full structural model was iteratively modified. The full model includes all exogenous variables, endogenous variables, measurement errors, and error variances in the computational model: structural equation modeling allows for analysis of the entire structure, including potentially nonzero covariances between latent constructs and between measurement errors. One modification was made from each iteration to the next based on the modification indices and theoretical justification for each change that was made. Additional indicators were also removed to improve the model fit and the variances were set equal to zero on all indicators with coefficients set equal to one, as mentioned previously, per standard practice. The process was iterated until no theoretically justifiable modification remained that would improve fit indices. This entire analysis of measurement model and full model was completed for both ways of imputing missing data.

Individual Discount Rate Estimation

Estimates of individual discount rates were calculated from responses to four questionnaire items, each of which revealed a discount rate equal to, larger than, or smaller than a certain percentage; two items examined rates for payments made and two items examined rates for gifts received. A simple analysis was completed in Microsoft Excel to code each response with its corresponding range of individual discount rates and then compare each record's values across items. Agreement or disagreement was evaluated, and in cases of agreement, an individual discount rate value or range was estimated for payment made and for gift received for each respondent. Based on all cases of agreement, averages across all records were calculated for payments made and for gifts received using point estimates or midpoints of ranges (with open ranges capped at 0% or 100% to create a midpoint). The average income for respondents was similarly calculated using midpoints of ranges and compared to individual discount rate literature to determine a literature-based estimated average individual discount rate for respondents.

Ethics and Human Subjects Research

No information collected in this study has inherent ethical challenges associated. An ethical study has been ensured primarily through informed consent of all participants, helping them to understand the costs (time) and benefits (access to research outcomes) of participating in the survey, explaining to them how their privacy would be protected, and assuring them that participation was entirely voluntary. No personally identifiable information was collected from respondents, and the "anonymize responses" feature in Qualtrics was used to remove IP address information from response data. No incentives were offered, so participants could not feel coerced into taking the survey by a large incentive. Finally, in addition to peer-reviewed publication, the outcomes of the research will be made accessible to participants via a web page whose location was publicized on the survey invitation and the questionnaire itself, and through future communication with local experts, so that respondents have an opportunity to see the results of the work they made possible and to benefit from the information collected.

This study was approved by the Institutional Review Board of The University of Texas at Austin with an exempt designation (study title "Homeowner Perceptions and Behaviors Surrounding Household Nitrogen Flows and Alternative Wastewater Management Technologies," study number 2014-09-0013). Everyone who was materially involved in executing the study, or who will have or might have access to the collected data, was included as a co-investigator on the study.

RESULTS AND DISCUSSION

Summary Statistics

Respondents proved fairly homogeneous on many demographic dimensions, as shown in Figure 5.2. Respondents were almost all white, non-Hispanic homeowners in Harwich, East Harwich, and Harwichport reporting on their primary home (important because Cape Cod has many vacation properties). In addition to the 88% of respondents who were homeowners, an additional 8% were "primary decision makers" for their homes because of their relationship to the owner or because of renting or leasing on a long-term basis. Most homes were serviced by conventional septic systems at the time of response. The participants were evenly split between men and women, and most had a bachelor's degree or advanced degree, making for a highly educated respondent pool. Participant age (see Appendix C) had a larger spread, with a mean of 64 years and a standard deviation of 12 years; annual household income (see Appendix C) also reflected a spread, with a median of the $75,000 - $100,000 category, the fifth percentile in the $15,000 - $25,000 category, and the ninety-fifth percentile in the $150,000 - $200,000 category. This group of respondents is similar to the population of Cape Cod as a whole (92.7% white, 52.4% female, 97% conventional septic system currently installed) though slightly more affluent and much more educated (median income $61,600).[30]

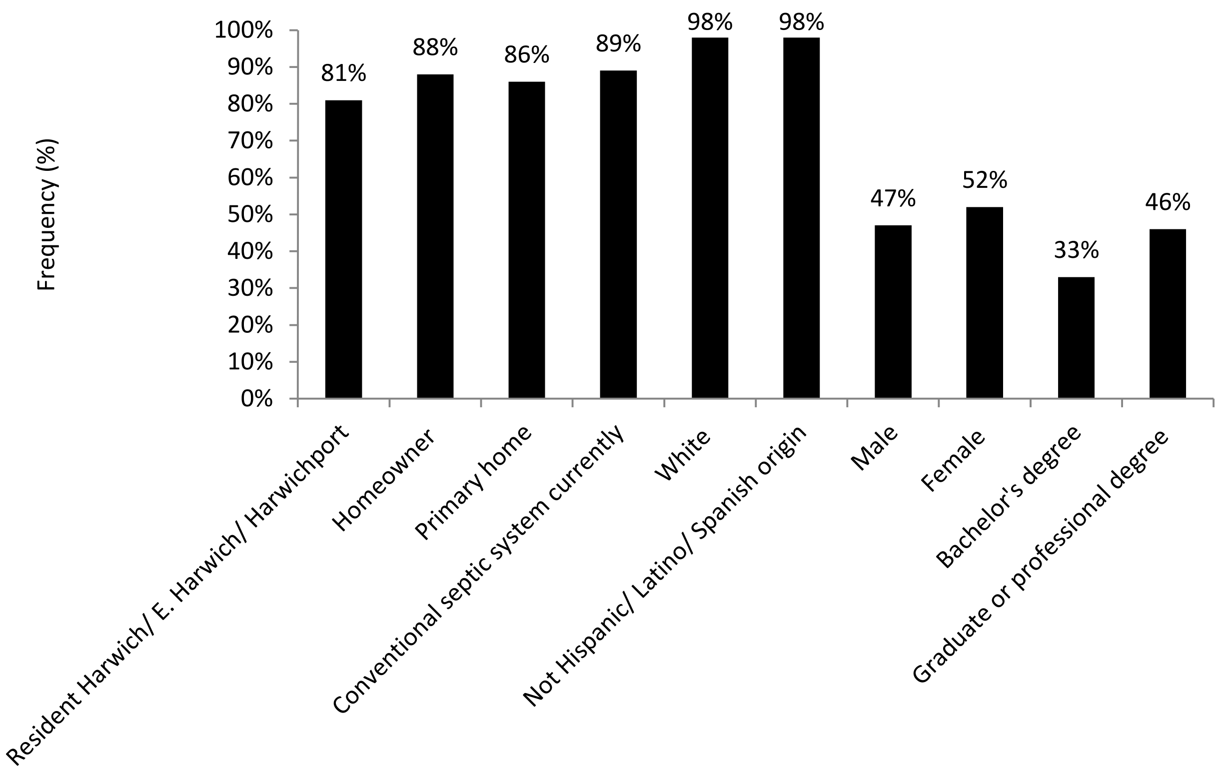

Figure 5.2. Summary of demographic information for respondents

Responses were more mixed for questions about current pollution on Cape Cod (see Figure 5.3). On a 7-point scale, with 1 = not a problem at all and 7 = a very significant problem, only 13% of respondents responded 1, 2, or 3, indicating a minimal pollution problem. Among respondents who perceive local water pollution as a problem (responses 5-7), there is disagreement about how significant the problem is. Respondents also disagree about the role that properly functioning conventional septic systems play in causing local water pollution, with respondents evenly split between disagree (responses 5-7) and agree/neutral responses (responses 1-4; see Figure 5.3, "Conventional septic perceived as source of pollution"); this result is in contrast to expert findings that conventional septic systems are the primary cause of the ongoing nitrogen pollution problem.[3] Most participants have not experienced significant direct effects from the pollution, with 66% reporting somewhere between "not affected at all" and the neutral point on the seven-point scale. There is also a split between participants who stated that local coastal water quality has gotten much worse in the last ten years (35%) and those who were not sure if or how the local water quality has changed (10% - see Appendix C). Thus in spite of a high education level across respondents, knowledge specific to the local pollution problem and its causes appears to be uneven. This information points to a need for education on the problem itself, its severity and importance, and the relative contributions from different pollution sources. While 28% of respondents reported having participated in a local workshop on the pollution problem and possible solutions, other avenues of education might be necessary to reach a much larger swath of the population.

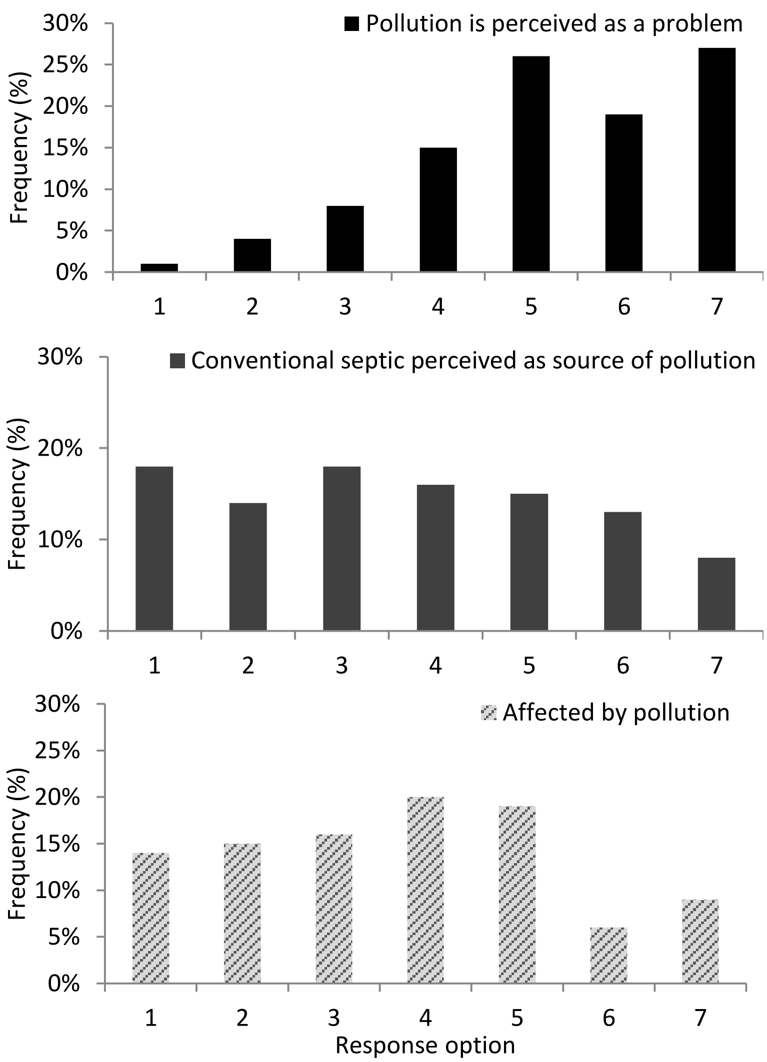

Figure 5.3. Responses to items on knowledge of issues

Notes: Items are 1) How much of a problem do you think water pollution is in your geographic region? (with responses 1 = not a problem at all to 7 = a very significant problem); 2) Please indicate how much you agree or disagree with this statement: "Ordinary or conventional septic systems (*i.e.*, not 'innovative' or 'advanced') do not contribute to local water pollution if they are functioning properly." (with responses 1 = strongly disagree, 4 = neutral, to 7 = strongly agree); 3) How much are you directly affected by water pollution (for example, property value, ability to swim or fish, tourism income, general enjoyment of the local environment, etc.)? (with responses 1 = not affected at all to 7 = very much affected)

Items querying willingness to use eco-toilets and to install them in one's own home provided surprising information as shown in Figure 5.4. Most respondents would be completely willing to use an eco-toilet in a friend's home (64%) and many would be completely willing to stay at a hotel or other short-term lodgings with eco-toilets installed (46%). Participants also expressed willingness to use eco-toilets at their workplaces, with 40% reporting either that they would always choose eco-toilets (if available) or they would choose eco-toilets whenever urinating (if available), and a further 18% reporting no preference between eco-toilets and "regular" toilets at the workplace (see Appendix C). However, the responses to "based on whatever knowledge you currently have (or don't have) of eco-toilets, would you be willing to install them in your home?" cluster around the neutral point on the seven-point scale (34%) with a second spike at "completely willing" (22%). While less positive than the other responses reflected in Figure 5.4, these results show a willingness to use and even install eco-toilets that has not been reflected in homeowner behavior on Cape Cod. This gap suggests that adoption rates could perhaps be increased if education efforts were undertaken; for example, 45% of respondents perceived a centralized wastewater treatment plant as the most effective wastewater system for improving water quality in local estuaries and bays (see Appendix C), even though centralized treatment systems might release more nitrogen into the local environment than technologies such as eco-toilets.[1,34–36] One respondent reported having eco-toilets already installed in the home.

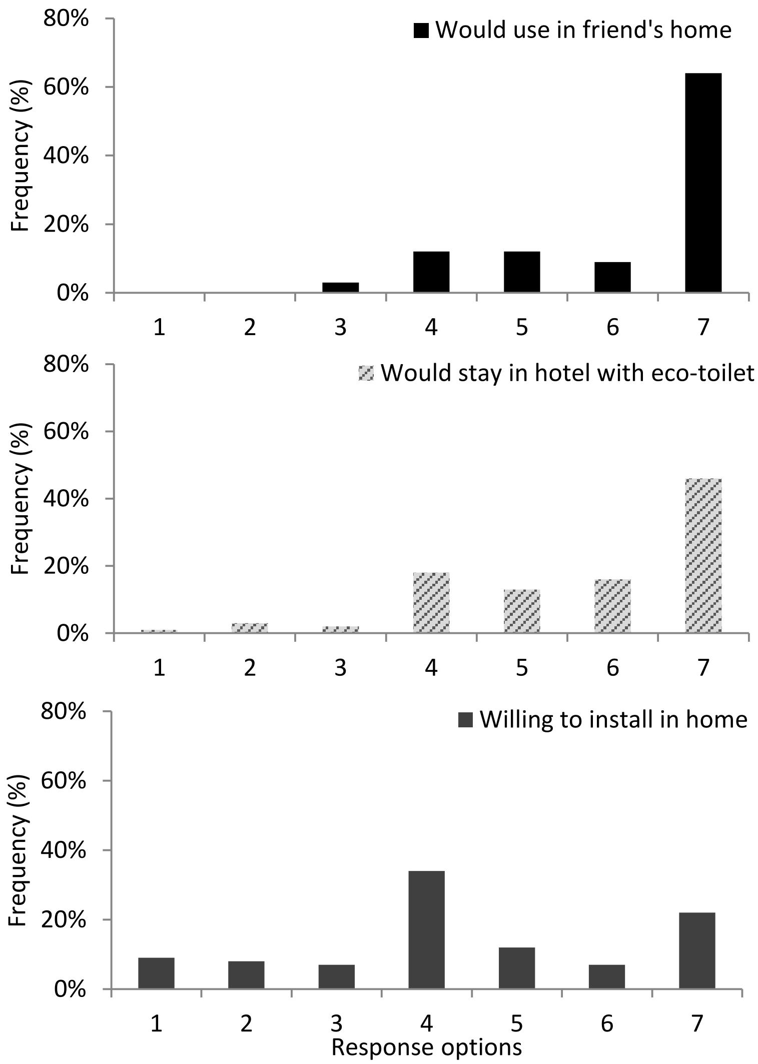

Figure 5.4. Responses to items on willingness to use or install eco-toilets
Notes: 1) Would you be willing to use an eco-toilet in a friend's home? 2) All else equal, would you be willing to stay at a hotel or rent temporary lodgings for a short time if the lodgings had eco-toilets installed instead of regular toilets? 3) Based on whatever knowledge and experience you currently have (or don't have) or eco-toilets, would you be willing to install them in your own home? (all with responses 1 = absolutely not, 4 = neutral, to 7 = completely willing)

More specifically, the gap between stated willingness to use eco-toilets and the extremely low adoption rates seen on Cape Cod might be explained in part by responses to two further sets of questionnaire items: 1) items examining the questions homeowners would want answered before making a decision to install eco-toilets in their own homes, and 2) items querying perceptions of the risks and benefits of eco-toilets. Respondents were asked to rank in order from "most important to have answered" to "least important to have answered" two groups of questions that might be relevant to eco-toilet adoption decisions, and the results are displayed in Figure 5.5. The questions in the first comparison group focused on logistics and the most frequent choices for “most important to have answered” were cost (29%), how the technology works (19%), and how collected waste is managed (13%). The questions in the second comparison group focused on other questions homeowners might have; the most frequent choices for “most important to have answered” were if there would be odor (32%), how property value might be affected (18%), and what health safeguards are in place (14%). Figure 5.5 further shows the proportion of respondents classifying each question as ranking first, second, or third in terms of “most important to have answered.” The prioritization of these questions suggests the most fruitful areas of focus for education efforts.

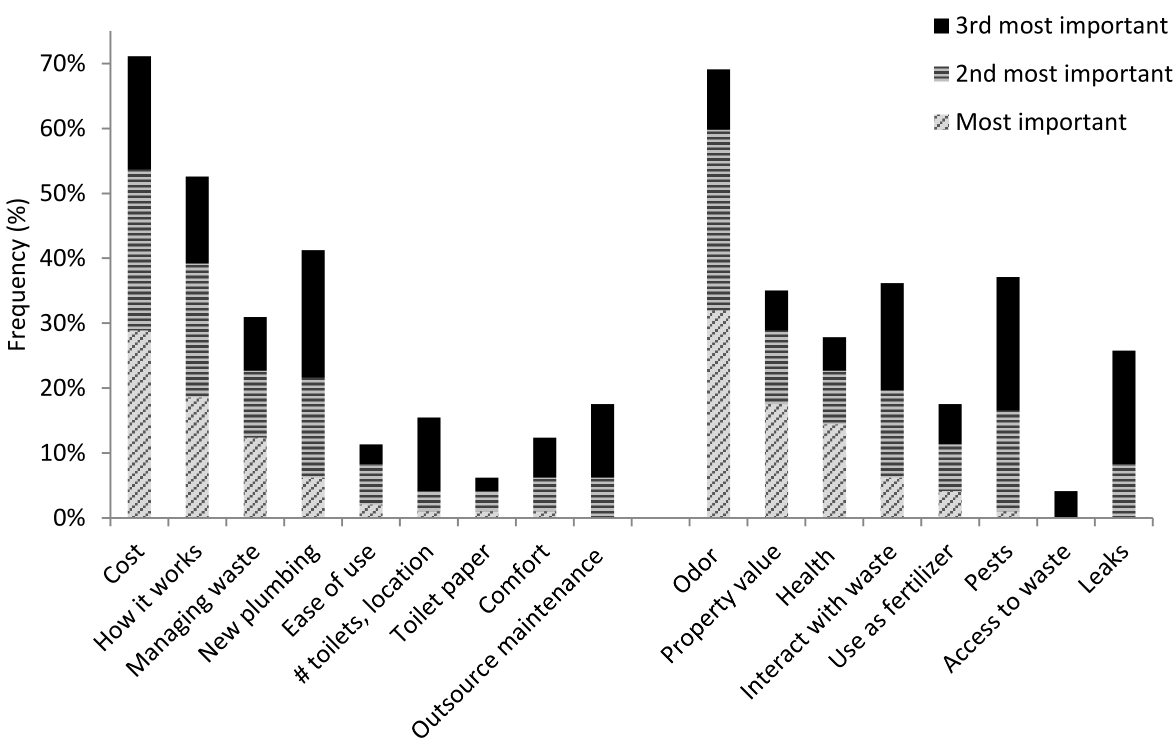

Figure 5.5. Questions homeowners might like to have answered before choosing to install eco-toilets in their homes

Notes: The nine questions on the left were in a single comparison group and the eight questions on the right were in a single comparison group. Questions within each comparison group were ranked from “most important to have answered” to “least important to have answered.” In the same order as displayed above, left to right: How much does it cost? How does it work? What do

I do with the collected waste? Can my existing plumbing be used? Is it easy enough that a child can use it properly, or a guest can use it without training? Are there limitations on the number or location of toilets? What do I do with toilet paper? Is it comfortable to use? Can I contract out the maintenance and how much would that cost? Will it smell? How will this affect my home's property value? What measures are in place to protect my and my family's health? Will I ever need to see or touch the collected waste? Can I use the collected waste as fertilizer? Will it attract insects or rodents? Can my children or my pets access the waste inside the container? How likely is it that the waste container will leak?

Participants also answered questions about the perceived risks and benefits of eco-toilets, and the tradeoff between risks and benefits (see Figure 5.6). Concerns about eco-toilets are an issue for some people, with 6% of respondents perceiving the "potential negative consequences of using eco-toilets in [the] home" as very severe or the adjacent category (6 on a 7-point scale); 20% reported that such risks were "not severe at all."Participants also appear to perceive the "potential positive consequences" as beneficial, with 25% choosing "very valuable" and only 1% reporting "not valuable at all." Perhaps most tellingly, responses were primarily neutral to the question of whether "the risks associated with eco-toilets are acceptable to obtain the benefits," with 32% choosing the neutral or midpoint response (4 on a 7-point scale). Respondents also classified any potential risks associated with eco-toilets between "completely old and familiar" and "completely new," with 44% choosing the neutral or midpoint response (4 on a 7-point scale). These results indicate that education about the potential consequences of using eco-toilets, both positive and negative, could help homeowners better understand the technology and potentially increase willingness to install it in the home.

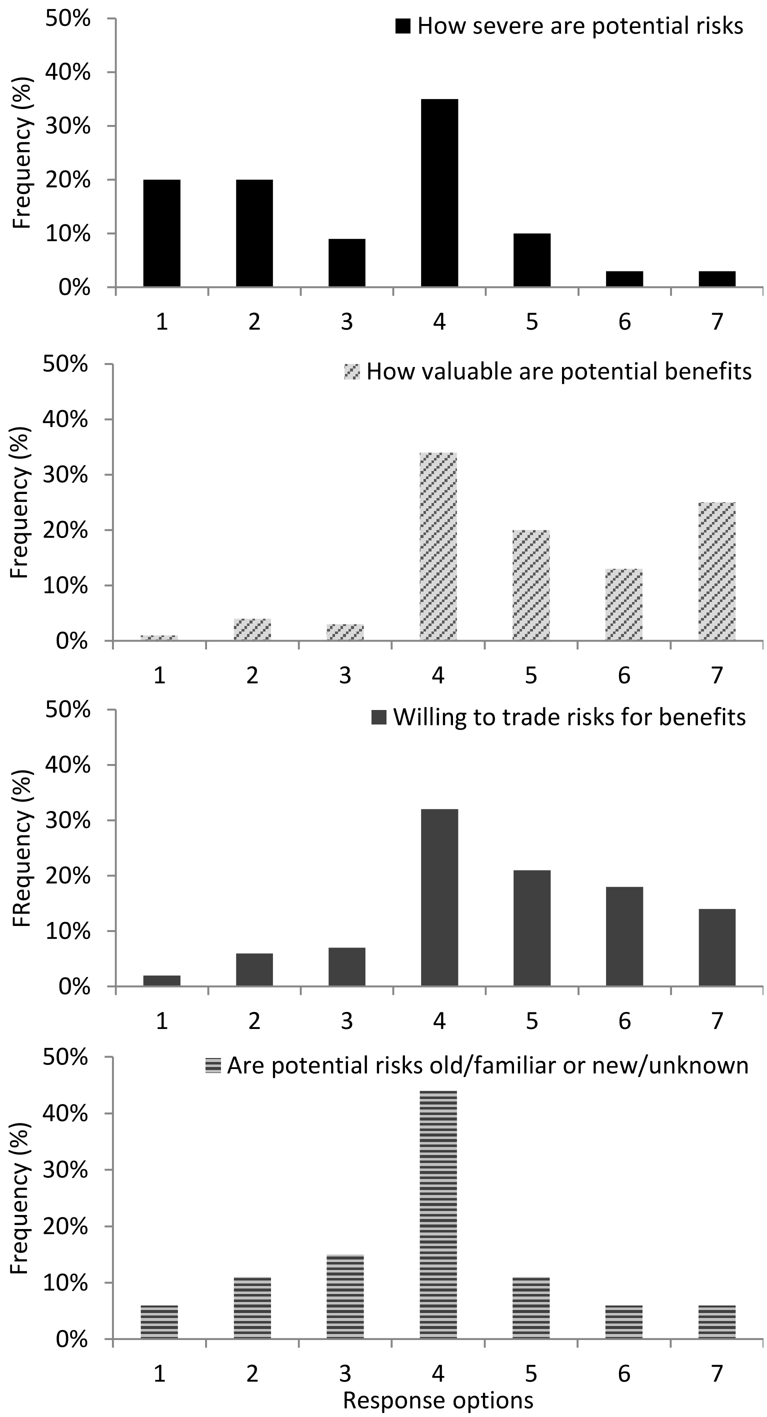

Figure 5.6. Responses to items on knowledge of action strategies
Notes: 1) How severe are the potential negative consequences of using eco-toilets in your home? (with responses 1 = not severe at all to 7 = very severe); 2) How valuable are the potential positive consequences of using eco-toilets in your home? (with responses 1 = not valuable at all to 7 = very valuable); 3) To what extent do you think the risks associated with eco-toilets are acceptable to obtain the benefits? (with responses 1 = not acceptable at all to 7 = completely acceptable); 4) To what extent do you think that any potential risks associated with eco-toilets

are new risks or old and familiar risks? (with responses 1 = completely old and familiar to 7 = completely new)

In spite of the respondents being highly educated, specific information about the pollution problem and the possible solutions was not well understood by all participants. At the same time, willingness to use eco-toilets in various settings and even install them in the home was higher than might be expected based on adoption rate to date. Together, these results suggest that public education efforts are likely to be effective in improving understanding and potentially increasing adoption rates of eco-toilets. Making the pollution problem more visible appears to be important, along with educating local residents on how they might be affected by the pollution both directly and indirectly. Education could also focus on the costs of installing and maintaining eco-toilets, how the technologies work (different variations on composting toilets and urine-diversion toilets are available), how collected waste must be managed, and what measures are in place to prevent unpleasant odors and to protect householders' health.

Data also show homeowners' concern about the effect of installing eco-toilets on property value. This issue is more difficult to address through educational campaigns because little is known at this point about what these effects will be. To answer this question in the future, data collection should begin immediately on property values before and after installation of eco-toilets for comparison and modeling of eco-toilets as a factor in housing price. However, early data on how eco-toilets affect property value might become irrelevant if eco-toilets become common in an area, so that much of the available housing stock has eco-toilets installed, or if infrastructure is put in place to support use of eco-toilets, such as municipal compost pickup service.

Structural Equation Modeling

Structural equation modeling allows for testing of hypothesized relationships between variables with freedom in the handling of variances and covariances. Iterative revision of the structural model produced a final computational model with significant lambda (coefficients on indicators) and gamma (coefficients on exogenous latent constructs) values, as shown in Figures

5.7 and 5.8. Modeling was repeated using two methods of imputing missing data: the expectation-maximization algorithm (EM model), and replacement of missing values with the mean of present data on the variable (means model). The final models from the two imputation methods showed only two differences: 1) the final EM model includes “Affected by N (nitrogen) pollution” as an indicator for “Knowledge of issues,” while the means model instead includes “Awareness of septic role in pollution” as an indicator for the same latent construct, and 2) the final EM model includes “Willing to use ET (eco-toilet) at work” as an indicator for “Attitudes,” while the means model instead includes “Current perceptions of ETs (eco-toilets)” as an indicator for the same latent construct. Figures 5.7 and 5.8 also show coefficient values for latent constructs (gamma values) significant at the 0.10 level. These values differ slightly between the EM model and the means model. However, because this modeling is based on a small sample of convenience, the results are best used to guide future research so the slight difference in the two models is not critical.

Modeling resulted in adequate but not excellent model fits for both methods of imputing missing data. Different indices indicate how well the model fits the data: 1) the chi-square value should be small and non-significant ($p > 0.1$) for a good model fit, 2) the adjusted goodness of fit index (AGFI) should be > 0.9 for a good fit and > 0.95 for an excellent fit, and 3) the root mean square error of approximation (RMSEA) should be < 0.05 for an excellent fit.[32,37] The EM model has a chi-square value of 80.72 with $p = 0.46$ (large p due in part to small sample size), an AGFI of 0.82, and an RMSEA of 0.0097. The means model has a chi-square of 106.29 with $p = 0.16$, an AGFI of 0.80, and an RMSEA of 0.039. Chi-square is strongly affected by sample size, with a smaller sample increasing the likelihood of a non-significant result, *i.e.*, increasing the appearance of good fit. The AGFI is also affected by sample size, with a smaller sample decreasing the AGFI value, *i.e.*, decreasing the appearance of good fit. In addition, AGFI is affected by parsimony, with increased parsimony leading to a higher AGFI. RMSEA is independent of sample size.[32]

These results suggest that knowledge of action strategies and age are both important determinants of willingness to install eco-toilets in the home, with knowledge of action strategies measured by indicators on perceptions of risks associated with eco-toilets. Other latent constructs that do not have significant gammas are not shown by this model to be important determinants of willingness to act, though results do indicate that some observed variables included here might be good indicators of these constructs. Because of the small sample size, it is impossible to draw firm conclusions about behavioral drivers of eco-toilet adoption; however, these results can direct future research in suggesting a model on which to build for further testing.

Future structural equation modeling in this area would benefit from inclusion of indicators present in the theoretical model proposed here but absent from the computational model. Additional indicators might also be appropriate, to provide better measurement of the latent constructs in the model. Because adoption of a household sanitation technology might differ substantively from adoption of other pro-environmental behaviors, the theoretical model could be modified to better fit the specific behavioral intention to install eco-toilets. For example, because household sanitation relates to hygiene, including indicators on personal hygiene attitudes or behaviors might improve the model. Finally, if larger numbers of U.S. homeowners begin to adopt eco-toilets, the model could be extended to incorporate the behavior itself rather than terminating at intention to act.

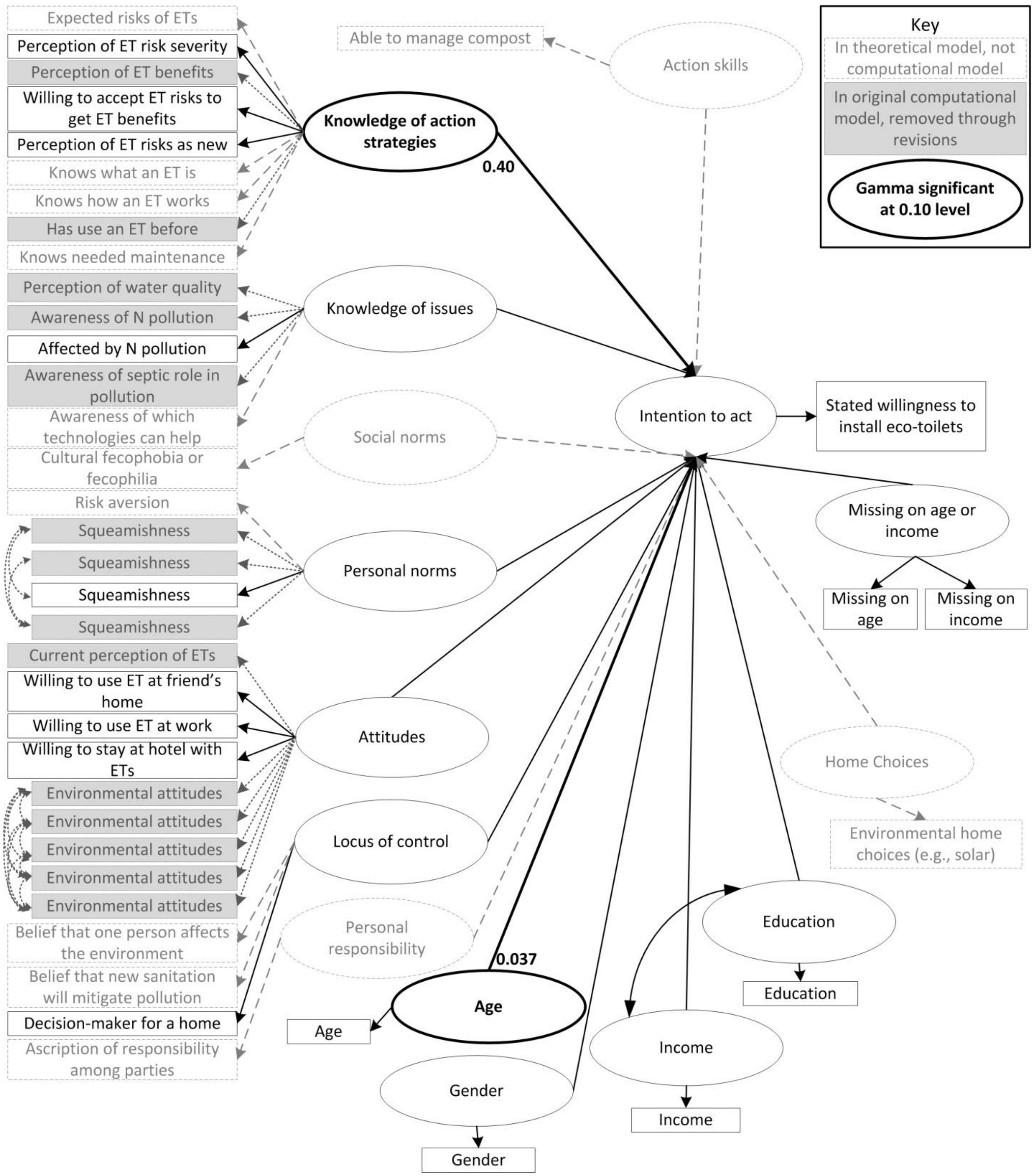

Figure 5.7. EM model: final structural model using the expectation-maximization algorithm to impute missing data.

Notes: N is nitrogen. ET is eco-toilet.

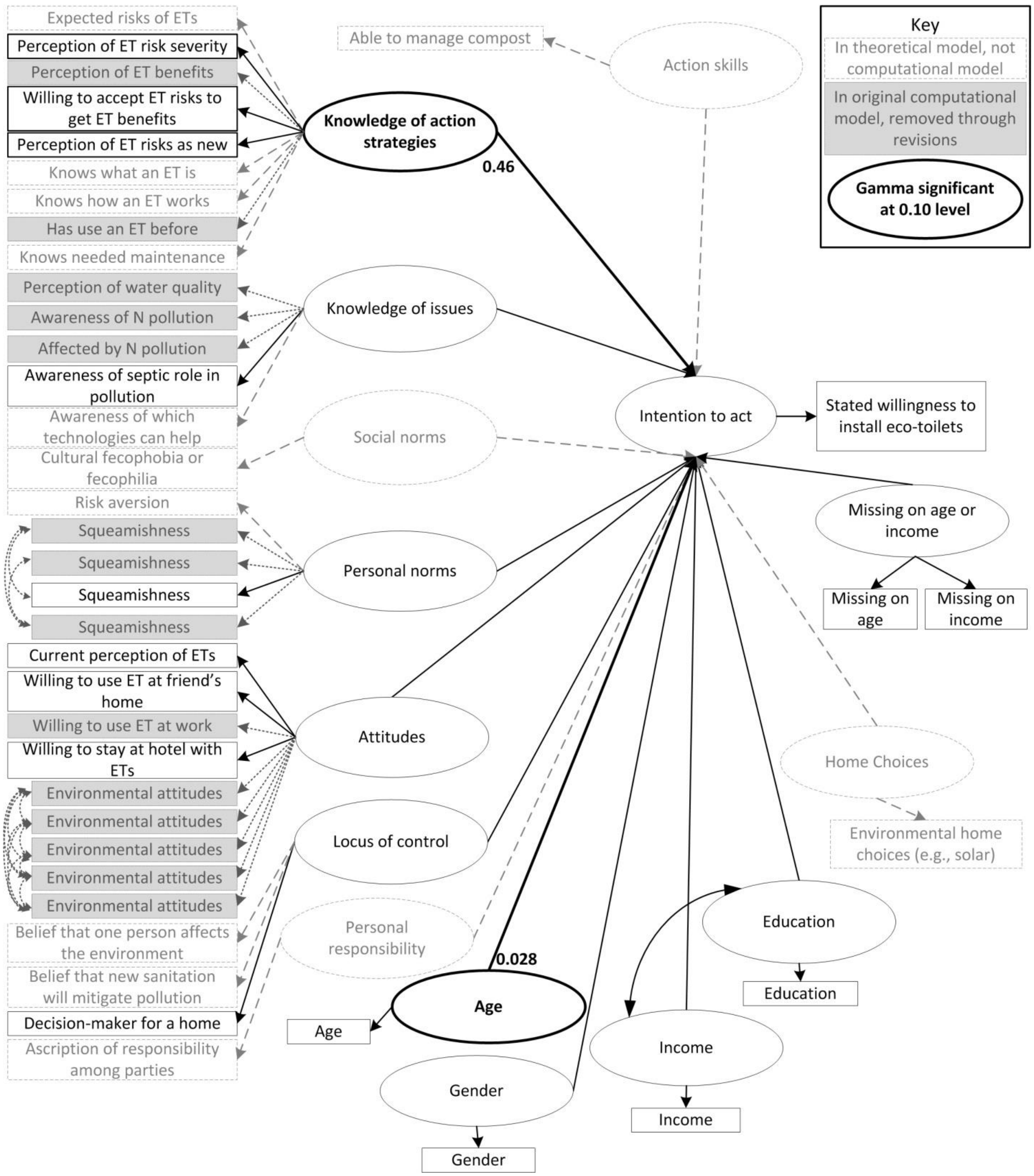

Figure 5.8. Means model: final structural model using the mean of existing data on the variable to impute missing data.

Notes: N is nitrogen. ET is eco-toilet.

Individual Discount Rate Estimation

In a previous study examining homeowner decision factors in eco-toilet adoption decisions, the individual discount rate was used as a proxy for those decision factors in life cycle cost calculations;[2] for comparison, individual discount rates were estimated from questionnaire response data. Questionnaire items examined both making payments and receiving gifts, so average individual discount rates were estimated for each: 12.4% and 1.7% respectively. These results emphasize that individual discount rates are likely to differ in different circumstances, such as when making a payment versus receiving a gift.

The average income for survey respondents (approximate, because data were collected for ranges rather than point values) was also compared to literature on energy-efficient home improvements to find an estimated average individual discount rate for survey respondents predicted from literature values: 14.9%. This value is approximately 20% higher than the individual discount rate estimated above for making payments; this discrepancy indicates that values predicted by literature might overestimate true individual discount rates. However, such predictions appear to be accurate at least to within an order of magnitude and are likely reasonable guidelines for interpreting ranges of expected outcomes based on individual discount rates in the absence of specific information on individual discount rates appropriate for given technologies. The discrepancy might also reflect the lack of specificity in income data collected (ranges rather than point values). Further research on this subject is needed.

Open-Ended Responses

Responses to open-ended questions reinforced themes found elsewhere in the data and provided some additional information. Lack of knowledge and need for education were apparent in a variety of responses. Some participants reiterated the idea that conventional septic systems are not the primary cause of the problem or that replacing conventional septic systems with eco-toilets would not solve the nitrogen pollution problem, with comments such as “don’t see the benefit over a properly operating septic system” and “I find it hard to believe toilets are the biggest contributor to the problems with Cape Cod's groundwater." Many responses reflect a lack of knowledge about and experience with eco-toilets, which participants want before choosing to install them in their homes: examples include "I would need to use an eco-toilet somewhere before I could give totally valid answers to these questions," "I have little to no experience with or knowledge of eco-toilets to make an informed decision about them," and "from what I read about eco-toilets, they are actually outhouses fashioned into the interior of the home." Educational efforts might not convince all homeowners to install eco-toilets in their homes, but they are clearly necessary to allow for informed decision-making and productive public conversation on the subject.

Two questionnaire items asking about the incentives respondents would demand in return for installing eco-toilets in their homes, either in an up-front lump sum or in a stream over time, revealed lack of knowledge and preferences both for and against eco-toilets. While some participants responded that all or some percentage of the cost of installation and maintenance must be paid for, many others responded "don't know" or "have no idea" or something similar. Others suggested very small incentive amounts, as low as $100, and a few responses suggested "0" or "none." On the other end of the spectrum, some responses made clear that the participants are skeptical of eco-toilets or could not be persuaded to install them: for example, "a lot," "would never do it," "they don't have that much money," and "$2 million." Educational efforts might convince some people to install eco-toilets, but such efforts will not persuade everyone to consider the technology a viable option.

A few open-ended responses referred to an issue that applies to Cape Cod but not to all U.S. communities: the population is aging, particularly those who live year-round in their Cape Cod homes. As one participant stated, "a large number of people living here on Cape Cod are retired and on fixed incomes, hence the cost to upgrade to an eco-toilet would be a huge obstacle." Other responses included "I'm 67 and the thought of keeping the waste in a container that has to be inside the house is hard to accept" and "I have arthritic knees which would make it hard to clean stand alone ETs [eco-toilets] and bury the compost in my yard." The demographic makeup of the community appears to be an important factor in the adoption of eco-toilets, with the aging population on Cape Cod less likely to accept these technologies than a younger population might be.

An unexpected result from some open-ended responses is that some participants appear to have perceived the survey itself as a tool for advocacy and education. The catch-all free response question at the end of the questionnaire garnered responses such as these: “please keep getting out information,” “I applaud your efforts to improve water quality,” and “I hope that this survey will help to educate people to conserve drinking water and to compost our waste.” The questionnaire was explicitly designed to avoid advocating for any particular technology or position; minimal information on eco-toilets and other technologies was provided, so that respondents would have a little basic information but would not be swayed by lengthy or biased informational statements. However, implementation of a survey alerts the participants to the study of the topic, which inherently raises awareness of the subject and might stir curiosity about the topic; this phenomenon is similar to the Hawthorne effect well known in the social sciences, in which the act of observation affects the observed (similar to the Heisenberg uncertainty principle in the physical sciences).[38] Participants appear to believe that the implementation of this survey implied that the researchers were attempting to prove the viability of eco-toilets. Future implementations of surveys on eco-toilets could further examine this issue, perhaps by providing topical information to one group of participants and none to another group.

Case Study

One individual on Cape Cod contacted the researchers directly after hearing about this study; she has composting toilets installed in her home and offered to discuss her experience and answer any questions. She reported having numerous problems with her toilets, including three floods of sewage because of improper installation and one electrical fire due to the vent fan and the new wiring it required (her planned solar powered fan was not permitted). She stated that she is very happy with the toilets now that the problems have been resolved. She also stated that she would not have installed them if she had known in advance about the problems she would have. She maintained that the technology is an excellent choice for Cape Cod, though she suggested that increased institutional support is necessary if eco-toilets are to be adopted on a large scale. This example illustrates the complexity of the issue, with even individuals in favor of adoption recognizing some significant challenges to making widespread adoption feasible.

Limitations and Future Research

This study did have some limitations, which could be addressed through further research: the development of the questionnaire was curtailed due to resource limitations and the data were collected from a sample of convenience. Typical questionnaire development would continue beyond the point at which this study has concluded. The questionnaire instrument would be analyzed and revised based on collected data, then the revised questionnaire would be used for full implementation. This process has begun through the structural equation modeling discussed previously. Model revisions should be reflected in the revised questionnaire before further implementation. If possible, the revised questionnaire should also reflect indicators included in the theoretical model but excluded from the computational model used in this study. After the questionnaire has been fully revised, a full implementation should be undertaken with random sampling to allow inferences to be drawn about the population based on the data collected. Such an implementation would require significant resources, which is why it was not included in the work to date. Future research could also examine the effects of including detailed information about eco-toilets, local pollution, or other relevant topics, for participants to read before completing the survey. Related research on how installation of eco-toilets affects property value will also be important for better understanding of the critical factors influencing adoption decisions.

Conclusions

This study is the first of its kind, surveying potential users of eco-toilets in the U.S. Results indicate topics for educational efforts and avenues for future research. In spite of an extremely low adoption rate thus far observed on Cape Cod, data collected suggest that willingness to install eco-toilets might be higher than expected and contingent on homeowners' understanding of the realities of living with eco-toilets.

Targeted education is likely to be useful in increasing adoption of eco-toilets, though it is unlikely to convince all homeowners to adopt these technologies. In spite of a high education level among respondents, data show varying levels of understanding about how much conventional septic systems contribute to the local nitrogen pollution problem and a relatively low level of knowledge about eco-toilets across participants. Educational efforts should focus on the costs associated with eco-toilets, how the technologies work, how collected waste is managed, whether unpleasant odors are likely, and what health safeguards are in place in these systems. Education might also be useful on the topics of potential risks and benefits of using eco-toilets, and on the pollution problem on Cape Cod. Nevertheless, some individuals will likely not be swayed by education, as reflected in responses such as requiring an incentive of "$2 million" in return for installing eco-toilets in the home.

Responses reflect poor perception of eco-toilets and yet high willingness to use them in settings such as the workplace, a hotel, and a friend's home. Participants were largely neutral on the question of installing eco-toilets in their own homes. Stated willingness to use or install eco-toilets seems to contradict the low rate of adoption seen thus far on Cape Cod. In addition to further education, adoption could perhaps be increased by offering larger incentives than those that have been offered thus far. Participants indicated that lack of knowledge is a deterrent to adoption and that incentives must compensate for much or all of the up-front purchase and installation costs, which would be larger than the offered incentives in most cases.

Future structural equation modeling with a revised model could lend further insight into the factors influencing intention to adopt eco-toilets. Model revisions should include examination of whether and how adoption of eco-toilets might differ from other pro-environmental behaviors. A sound behavioral model would suggest interventions likely to succeed in increasing adoption, both from an educational perspective and a policy perspective.

Individual discount rates estimated from collected data indicate that values from the energy-efficiency literature might skew high. Rates also appear to differ substantially between making payments (higher estimated rate) and receiving gifts (lower estimated rate). Further research is needed. Directed survey research could be used to elicit individual discount rates based on stated preferences regarding hypothetical eco-toilet purchases, or if a substantial market for eco-toilets develops, real purchase data could be used to calculate implied discount rates; both of these methods are commonly used with respect to energy-efficient technologies. Moreover, because of the unique situation on Cape Cod, an experiment could perhaps be undertaken to study this issue in a more controlled manner. Such an experiment would allow for study of many issues at hand here, in addition to individual discount rates.

Further research also is needed to extend this study and address some of its limitations, as well as to examine related issues such as the effect that installing eco-toilets might have on property values. Revision of the questionnaire should be completed and implementation with a larger, random sample should be undertaken with sufficient resources to support such an effort.

As the first survey of potential eco-toilet users in the U.S., this study has shed much-needed light on the gap between the technical potential of a sanitation system favored by many environmentalists and the willingness of homeowners to adopt an unfamiliar technology for a use that many consider extremely private. The results of this study suggest that efforts to increase adoption of eco-toilets are not entirely futile, but that much work must be done both to better understand homeowners' needs and wants for their household sanitation systems and to better educate homeowners about the technologies that might meet those needs in increasingly sustainable ways. Any policy requiring homeowners to install eco-toilets is likely to meet with substantial resistance, but educational efforts could pave the way to future policies encouraging or perhaps eventually requiring eco-toilets as a more sustainable household sanitation alternative than the currently most popular technologies.

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Chapter 6: Conclusions

Regardless of how technically brilliant a technology is, it cannot help solve a problem if its intended users reject it. In particular, decentralized household sanitation technologies depend on adoption by homeowners if they are to contribute to solving sewage-related problems. Drawing methods from a variety of disciplines in addition to engineering allows for more thorough understanding of technology uptake and barriers to adoption. Only as this more complex and comprehensive understanding is reached can uptake be increased, allowing technologies to succeed in their roles in solving sustainability problems.

This dissertation contributes both knowledge and methodology to the literature and accomplishes its goal of illustrating how a multidisciplinary approach improves understanding of potentially sustainable solutions to engineering problems. The first stage of research presented a life cycle cost comparison of a set of decentralized sanitation technologies with parametric sensitivity analysis to examine uncertainty and variability. This stage also included a nitrogen mass balance at the household scale, which was not previously available in the literature. The second stage of research introduced the threshold analysis method for examining expected outcomes based on ranges of individual discount rates when such rates are not known for the technology in question; individual discount rates were used here as a proxy for individuals' decision factors in the two-party decision about adopting a decentralized technology. Both stages one and two reported expected outcomes for case study areas that can be used to inform policy decisions in those locations and to guide similar analyses in other locations. The third stage of research presented the first household survey on adoption of eco-toilets by U.S. homeowners. Together, these stages of research have demonstrated the importance of a multidisciplinary approach in examining "sustainable" technologies.

In the initial life cycle cost and cost-effectiveness analysis for the Falmouth, Massachusetts case study, flush diversion toilets with conventional septic systems for greywater management were found to be the lowest cost option and the most cost-effective relative to nitrogen management in household wastewater. Composting toilets paired with conventional septic systems and innovative/advanced septic systems also emerged as attractive options under some scenarios. Centralized wastewater treatment with gravity sewer collection was shown to be the most expensive and least cost-effective option across all scenarios. On-site greywater recycling proved to be more expensive than using a conventional septic system to manage greywater. Results were found to be robust across a range of scenarios and uncertainties.

The individual discount rate was used as a proxy for factors affecting individuals' decision-making in the two-party (individual and municipality) decision to adopt decentralized household sanitation systems. A threshold analysis method was developed to delineate ranges of expected outcomes based on individual discount rate threshold values, because such rates are not known for sanitation technologies and are difficult to examine directly at this time due to a lack of purchase data coupled with relevant information. Rates related to adoption decisions for energy-efficient technologies were used as a guide in interpreting the thresholds calculated and their implications for incentivizing adoption for case studies in Falmouth, Massachusetts and in the Allegheny County Sanitary Authority (ALCOSAN) service area near Pittsburgh, Pennsylvania. When the individual discount rate was incorporated, the life cycle cost comparison of household sanitation systems became more complex than was found in the conventional life cycle cost analysis in the first stage of research. Results showed that decentralized systems are expected to be chosen by individuals under some scenarios in Falmouth without any incentive required and under other scenarios only if an incentive is paid. According to results for the ALCOSAN area, decentralized systems are not expected to succeed in most examined scenarios; in those under which decentralized systems are likely to be adopted, incentives are not expected to be required. Thus the inclusion of the individual as a decision-maker in the decentralized technology adoption process illuminated important complications in the comparison between systems, complications that might lead to greater understanding of why decentralized sanitation systems might not be widely adopted in spite of technical potential.

The first household survey of U.S. homeowners' perceptions of eco-toilets (composting and urine-diversion toilets), in the context of potential adoption in the home, revealed important gaps in knowledge and surprising inconsistencies between willingness to use and to adopt eco-toilets and observed adoption rates. While further research with expanded survey samples is critical to allow for extrapolation of results to larger populations, the data collected indicated areas in which education is likely to be fruitful in furthering the public conversation about eco-toilet adoption: lack of knowledge was found to be a clear deterrent to adoption. Rough approximations of individual discount rates based on collected data suggested that rates drawn from energy-efficiency literature (adjusted for the individual's income) might be slightly higher than true rates; more thorough and specific data are needed before clear conclusions can be drawn. Further examination of the underlying behavioral structure of the adoption decision is also needed, as non-monetary factors were clearly shown to critically influence such decisions. Including non-monetary factors further complicated the understanding of the potential for eco-toilets to address a sanitation-driven pollution problem in a sustainable way.

As intended, the progression from stage one through stage three of this research has shown that incorporating methods from multiple disciplines begins to illuminate critical complications in adoption decisions for decentralized sanitation technologies. Results from the conventional engineering analysis in stage one appear straightforward, with recommendations on which technologies can address a nitrogen pollution problem in Falmouth, Massachusetts at lowest cost and highest cost-effectiveness. Results from stage two present a less clear picture, when concepts from economics are brought to bear, with different outcomes expected for different cost scenarios and for individuals with different levels of income. Stage three, drawing from sociology and psychology, introduced further complications that begin to illuminate non-monetary factors affecting adoption decisions for technologies (eco-toilets) that are especially unfamiliar to most U.S. homeowners, with personal characteristics such as knowledge and age playing vital roles that are not captured in the preceding analyses. The consumer's willingness to use the technology, along with his/her expectations or requirements for monetary incentives, critically influence adoption rates of decentralized sanitation technologies. These factors likely hold similar sway over adoption of other decentralized technologies that might have great technical potential but that are not easily accepted by consumers. This case study in sanitation thus has illustrated the importance of drawing methods from disciplines beyond engineering to better understand the adoption of technologies that promise “sustainable” solutions to pressing problems. Economics, sociology, and psychology are a few of the disciplines that can be drawn on to better understand individuals’ technology adoption decisions; for example, educational theory could be used to better understand how people learn about unfamiliar technologies, methods from geography could lead to better understanding of people’s relationships with their local environments, and the process of reaching community consensus might be fruitfully examined through the methods of political science.

The question of sustainability remains. As discussed in Chapter 2, “if more sustainable options are to be promoted, the following questions have to be addressed jointly: What are more sustainable practices? What are the conditions that might keep people from adopting more sustainable practices and what are conditions that might support them in adopting such practices? Are there effective strategies to overcome these restrictions?”[1] The first stage of this dissertation’s research indicated that various decentralized technologies are more sustainable than centralized wastewater treatment, at least with respect to managing nitrogen pollution in a sensitive coastal environment. The remaining stages of research considered the conditions that keep people from adopting these technologies, both monetary and non-monetary, and suggest some strategies that might overcome these issues. Conventional engineering methods cannot answer all three of these questions, but a collection of methods from different disciplines can begin to answer them; additional methods, and further research with these methods, will provide more answers.

Ultimately, as Costanza and Patten point out, “sustainability” is a prediction of the future.[2] No researcher can definitively predict what will be sustainable, because future conditions cannot be known in the present, only guessed at through series of well-informed, scientificallybased predictions. This dissertation has limitations in the geographical boundaries drawn to make the analyses tractable as well as in this inherent challenge of sustainability analysis. In spite of these imperfections, this work sheds critical light on how the science and engineering community might continue to improve its predictions of sustainability by collaborating with other disciplines to better understand the full complexity of both the problems faced by today's global society and their potential solutions.

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Appendix A: Supporting Information for Chapter 3[5]

WATER BALANCE

Our water balance is based on household water usage data from the EPA,[1] which gives the allocation of water usage per capita across various household end uses. These EPA data are applicable to homes with conventional wastewater treatment technologies (WWTP or septic systems). All other treatment technologies studied require less water for proper operation; we thus reduce usage accordingly, based on data and assumptions below.

- All houses lose the same volume of water to leaks, regardless of wastewater technology.
- Vacuum toilets use 10% as much water as standard toilets, *i.e.*, 0.3 gallons per flush.
- Flush diversion toilets use 2% as much water as a standard toilet to flush urine only and 50% as much water as a standard toilet to flush solids. Urine-only flushes account for 2/3 of flushes.
- The two previous assumptions are based on the following references: 2–6.
- Greywater is recycled from showers and clothes washers and is used for clothes washers and toilets. Based on the volumes for these end uses, recycled greywater meets 100% of the need for clothes washing and toilet flushing in all scenarios with greywater recycling.
- Shower, faucet, and "other" usages are the same regardless of wastewater treatment technology. In other words, we assume that people do not change their other water usage habits regardless of what wastewater technology is implemented.
- In all cases the "base volume" is the volume of water included in the base water supply rate according to a Falmouth Water bill.[7] The base volume and base rate are assumed to correspond to the fixed costs of potable water supply.

$$base\ volume: 10.96\,\frac{ft^3}{hh-d} \times 70\%\ for\ indoor\ use \div 1.435\,\frac{c}{hh} \times 7.48\,\frac{gal}{ft^3} = 40\,\frac{gal}{c-d}$$

[5] Wood, A.; Blackhurst, M.; Hawkins, T.; Xue, X.; Ashbolt, N.; Garland, J. Cost-Effectiveness of Nitrogen Mitigation by Alternative Household Wastewater Management Technologies, Supporting Information. J. Environ. Manage. 2015, 150 (1), 344–354

- The "surplus usage" is the total usage minus the base volume. The surplus usage and associated cost are assumed to correspond to the variable costs of potable water supply.

The water balance is summarized in Table A1.

Table A1. Water Balance, in Gallons per Capita per Day, for Alternative Systems, with (1 and 2) WWTP and I/A Septic Systems as Baseline.
Notes: Systems: 1. WWTP, 2. I/A Septic System, 3. Flush Diversion Toilet with Conventional Septic System, 4. Dry Diversion Toilet with Conventional Septic System, 5. Dry Diversion Toilet with Greywater Recycling System, 6. Composting Toilet with Conventional Septic System, 7. Composting Toilet with Greywater Recycling System, 8. Blackwater Digester with Conventional Septic System, 9. Blackwater Digester with Greywater Recycling System.

System → Water use ↓	1 & 2	3	4	5	6	7	8	9
Toilet	18.69	3.36	0	0	0	0	1.87	0
Shower	11.76	11.76	11.76	11.76	11.76	11.76	11.76	11.76
Faucet	10.99	10.99	10.99	10.99	10.99	10.99	10.99	10.99
Clothes washer	15.19	15.19	15.19	0	15.19	0	15.19	0
Other	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71
Leaks	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59
Total Usage	69.93	54.60	51.24	36.05	51.24	36.05	53.11	36.05
Surplus usage	29.93	14.60	11.24	-3.95	11.24	-3.95	13.109	-3.95
Surplus usage as % of packages 1 & 2	100%	48.8%	37.6%	0%	37.6%	0%	43.8%	0%

NITROGEN FLOWS

The following data sources and assumptions were used in analysis of nitrogen flows. Table A2 shows final values used in calculating ranges for sensitivity analysis.

- Conversions between units of milligrams per liter and kilograms per capita were calculated assuming 70 gallons or 265 liters of water per capita per day,[1] based on indoor water use that would enter a sewer or septic system in a conventional treatment scenario.
- A typical amount of nitrogen in human excreta is 13 grams per capita per day or 4.75 kilograms per capita per year.[8] The amount of nitrogen can range from 3.7 kg to 7.1 kg per capita per year.[9–11]

- Short *et al.*[12] report a 1.67% average N_2O emissions factor for gravity sewer systems.
- Gerardi[13] indicates that 29% of the nitrogen that reaches a WWTP remains in the sludge after treatment.
- Meinzinger[14] reports that 85% of nitrogen in human excreta is in urine and 5% loss to evaporation during urine storage.
- Liquid effluent from a WWTP contains 5 milligrams per liter nitrogen.[15]

Table A2. Nitrogen Flow Values: Low Case, Base Case, and High Case.
Notes: All units are kilograms of nitrogen per capita per year.

	Volatilized as NH_3 or N_2O			Liquid Effluent			Nitrogen Removed from Watershed		
Item Name	Low Case	High Case	Base Case	Low Case	High Case	Base Case	Low Case	High Case	Base Case
compost toilet/installed	0.10	0.30	0.20	0	0	0	3.4	7.0	4.5
diversion toilet/installed	0.10	0.30	0.20	0	0	0	3.4	7.0	4.5
WWTP & gravity sewer/installed	0.040	0.12	0.079	0.24	0.72	0.48	2.9	6.8	4.2
digestion plant & pressure sewer	0	0	0	0	0	0	3.7	7.1	4.7
I/A septic /installed	0	0	0	0.73	2.2	1.5	1.5	6.4	3.3

COST DATA

Table A3. All cost data, sources, and assumptions used in the cost and cost-effectiveness analyses.

Cost Item	Capital Cost (low case / base case / high case)	Capital Cost References	O&M Cost (low case / base case / high case)	O&M Cost References	Notes and Assumptions
WWTP and gravity sewers	$46,320 / $47,850 / $49,380	16,17	$290 / $500 / $720 WWTP $320 / $400 / $480 sewer	18,19	Assumes 100 gallons per person per day, 1.4 people per home in Falmouth.
I/A septic systems	$6,110 / $13,400 / $25,000 new $6,110 / $12,480 / $25,000 retrofit	12,20–25	$550 / $950 / $1,750	23,25–27	Includes costs for Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics.
standard toilet	$260 / $510 / $810	28	$0 / $10 / $100	assumed	Includes multiple mounting options. O&M assumes one $100 servicing every 10 years for base case, annual $100 servicing for high case, no maintenance for low case.
urine-diversion toilet	$850 / $1,210 / $1,440 toilet $2,670 / $3,200 / $4,170 tank	3,28–30	$130 / $170 / $220 flush $195 / $280 / $360 dry	31	Includes dry and flush toilet options. Installation costs are 'bare labor.' Assumes 500-gallon urine tank (⅓ of standard septic tank), located outdoors. Flush toilet O&M is ⅔ of septic O&M cost, assuming some fixed costs. Dry toilet O&M comes from flush toilet O&M and compost toilet O&M.
compost toilet	$6,150 / $8,340 / $10,530	28,32	$100 / $150 / $200	33,34	Includes dry toilet and foam flush options, two sizes of composter. Installation costs are 'bare labor.' Capital costs are for a pair of toilets with one compost container.

Table A3, continued

blackwater digesters and pressure or vacuum sewers	$8,450 / $9,710 / $10,960	35	$500 / $640 / $780	35	Euros converted to USD at €1 to $1.37. Includes pressure and vacuum sewer network options.
vacuum toilet	$530 / $810 / $1,320	35–39	$0 / $10 / $100	assumed	Euros converted to USD at €1 to $1.37. Installation is 'bare labor.' O&M assumed same as standard toilet.
conventional septic system	$8,000 / $9,590 / $12,500	28,40	$190 / $260 / $330	41,42	All new tanks in Massachusetts are required to be 1,500 gallons; some legacy tanks are 1,000 gallons. Assumes annual pumping to be conservative.
retrofitting or upgrading an existing septic system	$0 / $4,500 / $9,000 usable $2,000 / $10,000 / $18,000 failing	40,43	--	--	Includes using existing tank as-is, upgrading existing tank, filling or removing existing tank and installing a new one.
greywater recycling system	$4,450 / $5,250 / $11,570 $8 / $35 / $94 per linear foot of piping	28,44	$320 / $760 / $1,780	44	Australian dollars converted to USD at $1AUS to $0.89. Costs for Nubian, Perpetual Water, Clearwater Aquacell, and Rootzone vertical filter systems
variable drinking water supply cost	--	--	$40 / $41 / $50	7,45	Uses rate for excess usage on household bill. Range for sensitivity analysis comes from Falmouth budget line DPW Water Utilities Other Expenses for two years.
decentralized monitoring	--	--	$28 / $35 / $47	assumed	Assumes $70,000 per year for one inspector, 6-10 inspections per day, working 250 days/year.
removal of existing standard toilet	$80 / $140 / $200	46	--	--	

SENSITIVITY ANALYSIS

Tornado charts are shown in Figures A1-A9. The ranges shown reflect both parametric uncertainty, with ranges of model inputs shown on the ends of each bar, and model (structural) uncertainty with respect to the condition of existing septic system: all systems functional, all systems failing, and 20% failing.

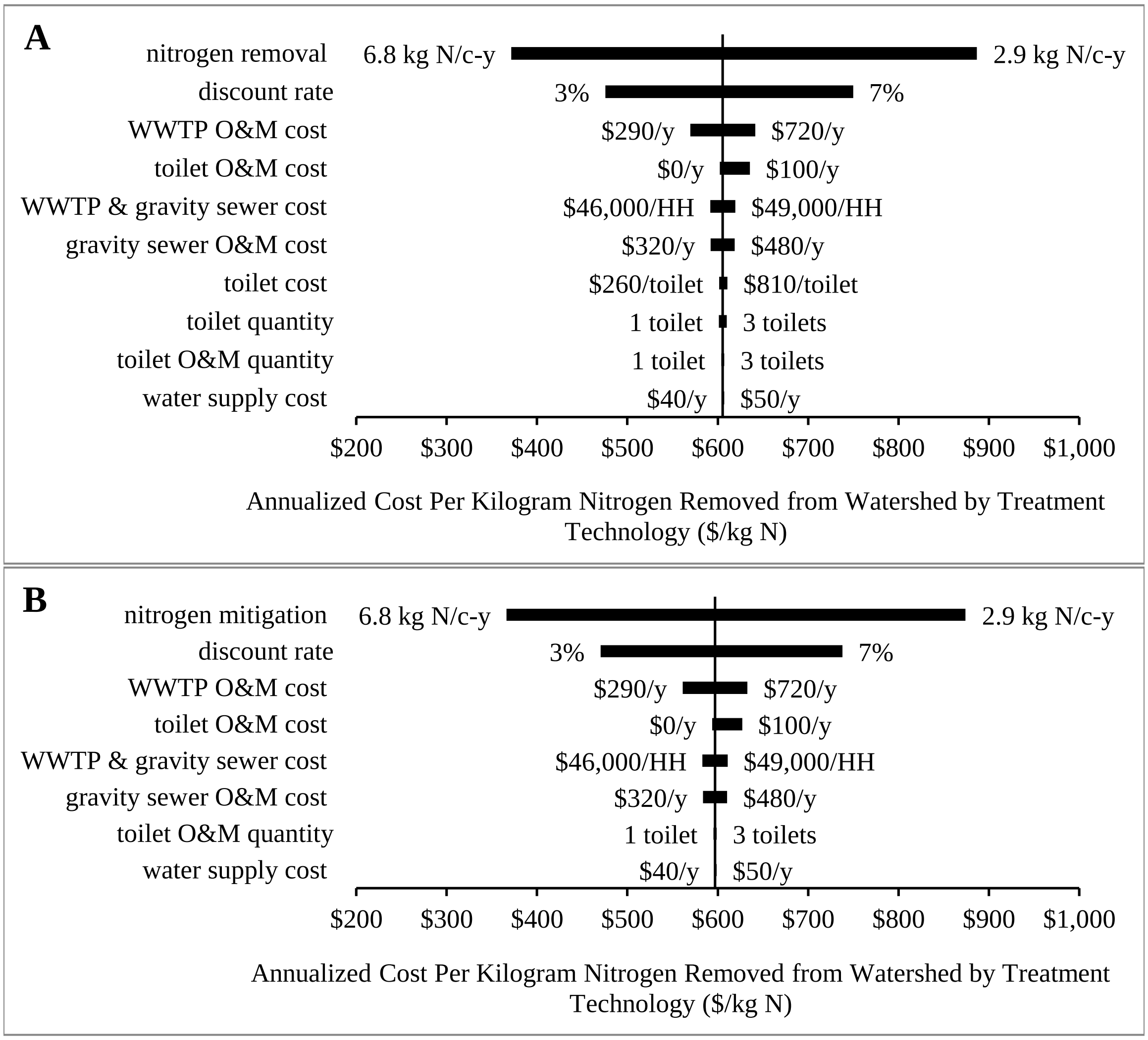


Figure A1. Sensitivity to various factors of cost-effectiveness of a wastewater treatment plant (WWTP) for (A) new construction, and (B) retrofits of existing homes.

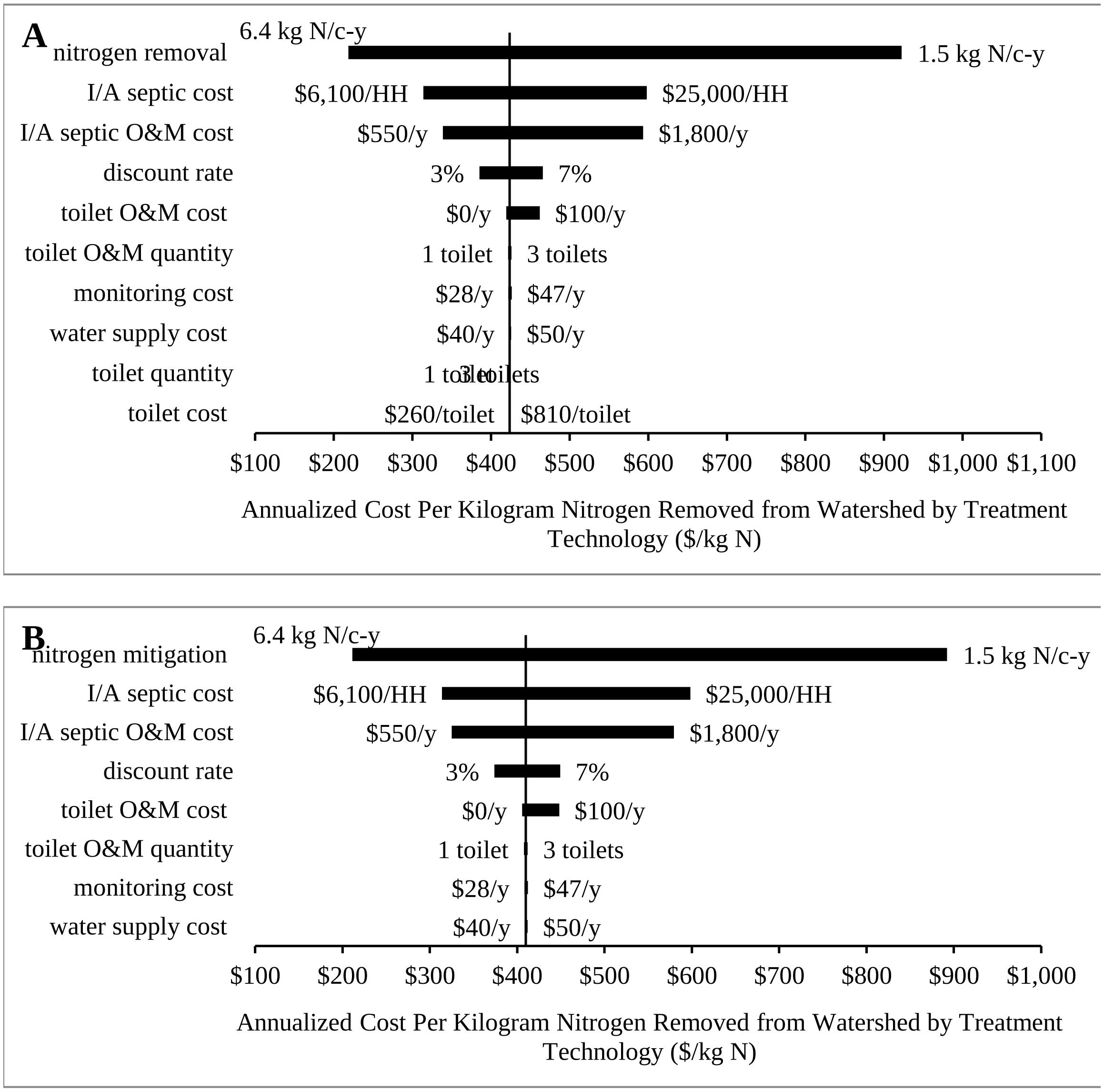
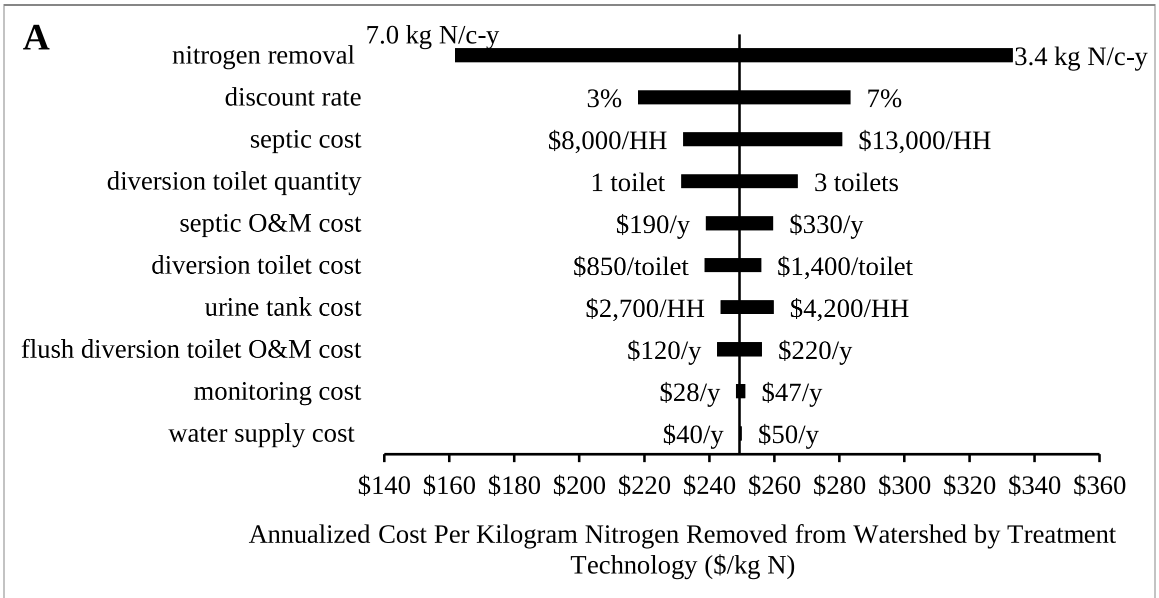
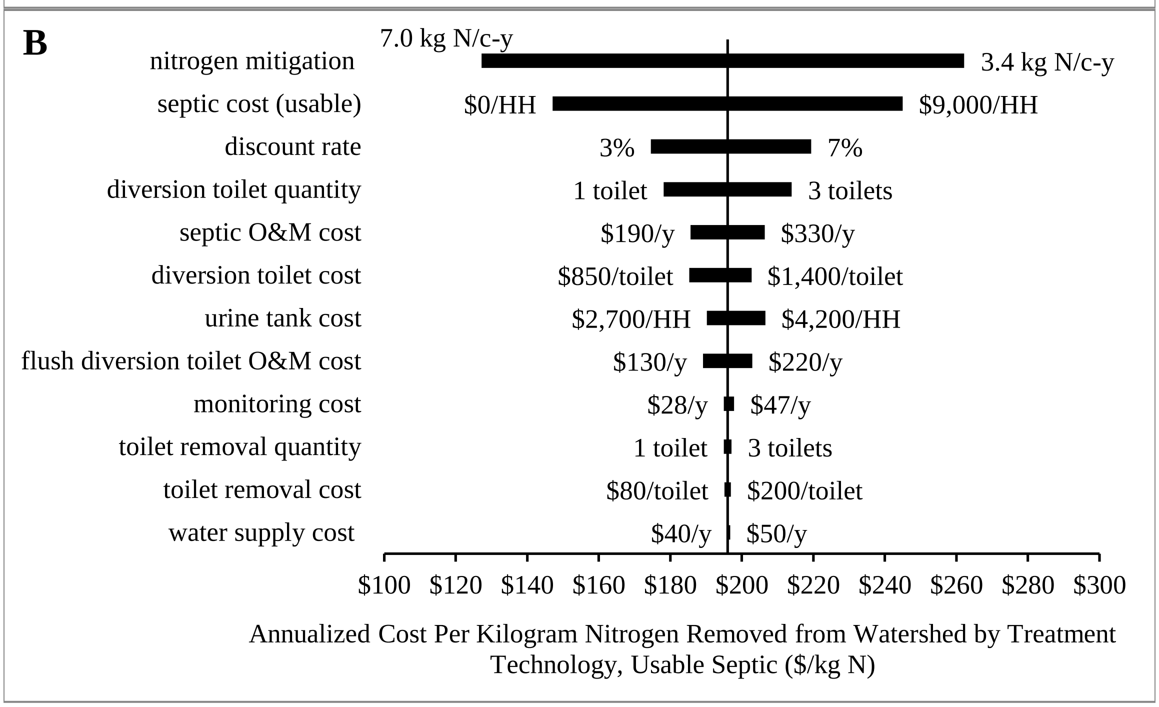


Figure A2. Sensitivity to various factors of cost-effectiveness of innovative/advance septic systems (I/A septic) for (A) new construction, and (B) retrofits of existing homes.



A
nitrogen removal
discount rate
septic cost
diversion toilet quantity
septic O&M cost
diversion toilet cost
urine tank cost
flush diversion toilet O&M cost
monitoring cost
water supply cost
7.0 kg N/c-y
3.4 kg N/c-y
3%
7%
$8,000/HH
$13,000/HH
1 toilet
3 toilets
$190/y
$330/y
$850/toilet
$1,400/toilet
$2,700/HH
$4,200/HH
$120/y
$220/y
$28/y
$47/y
$40/y
$50/y
$140 $160 $180 $200 $220 $240 $260 $280 $300 $320 $340 $360
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology ($/kg N)



B
nitrogen mitigation
septic cost (usable)
discount rate
diversion toilet quantity
septic O&M cost
diversion toilet cost
urine tank cost
flush diversion toilet O&M cost
monitoring cost
toilet removal quantity
toilet removal cost
water supply cost
7.0 kg N/c-y
3.4 kg N/c-y
$0/HH
$9,000/HH
3%
7%
1 toilet
3 toilets
$190/y
$330/y
$850/toilet
$1,400/toilet
$2,700/HH
$4,200/HH
$130/y
$220/y
$28/y
$47/y
1 toilet
3 toilets
$80/toilet
$200/toilet
$40/y
$50/y
$100 $120 $140 $160 $180 $200 $220 $240 $260 $280 $300
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology, Usable Septic ($/kg N)

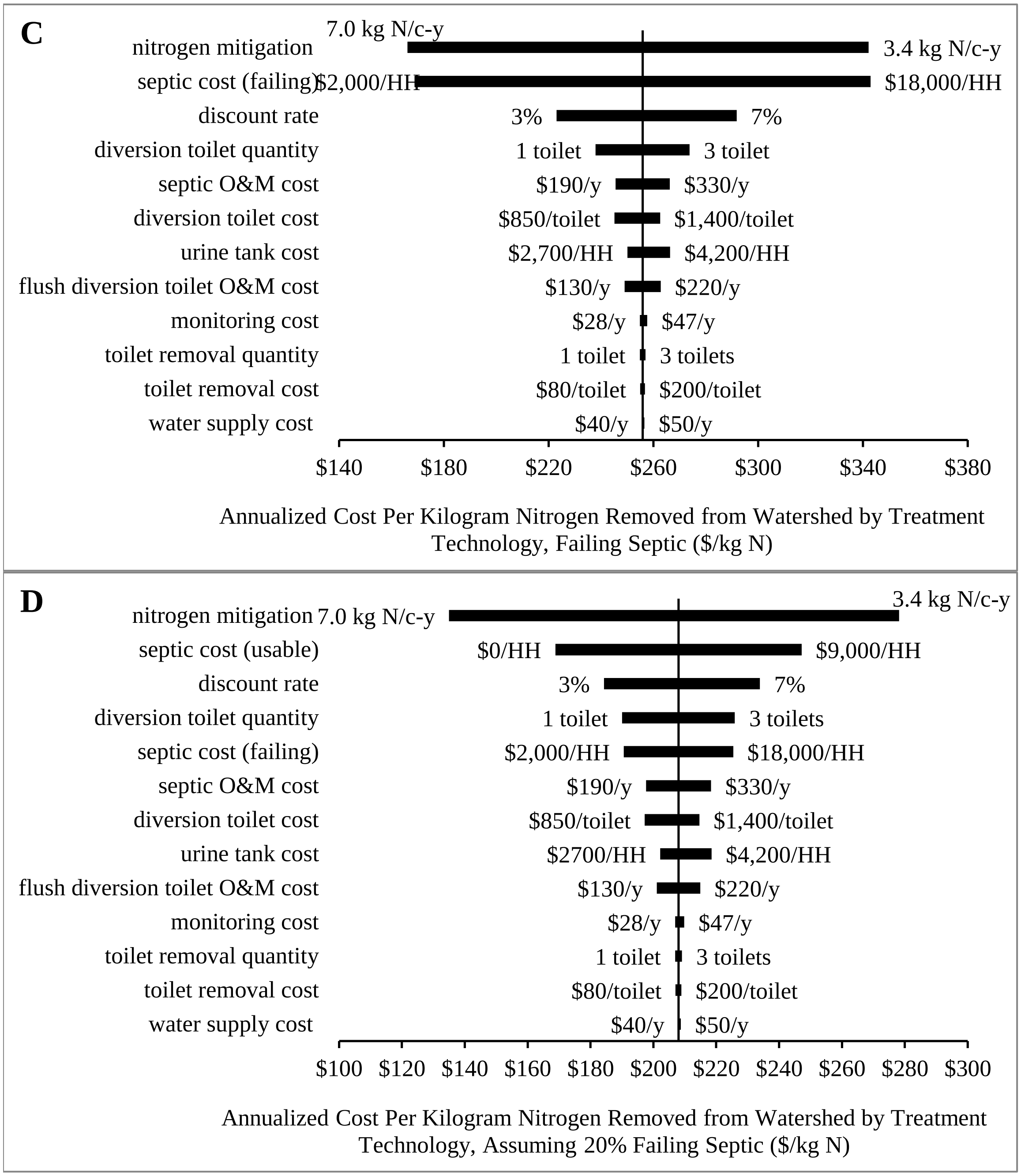
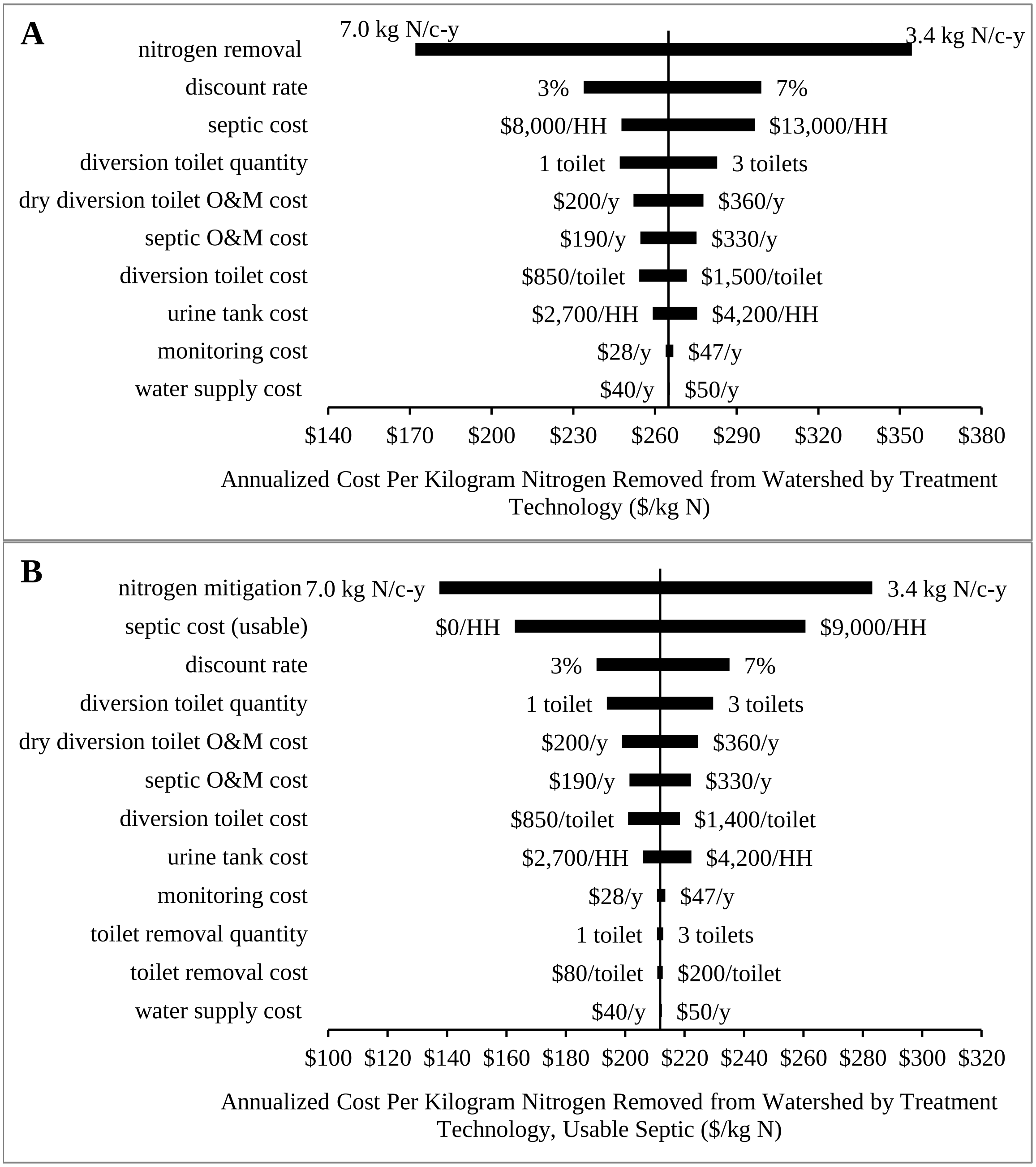
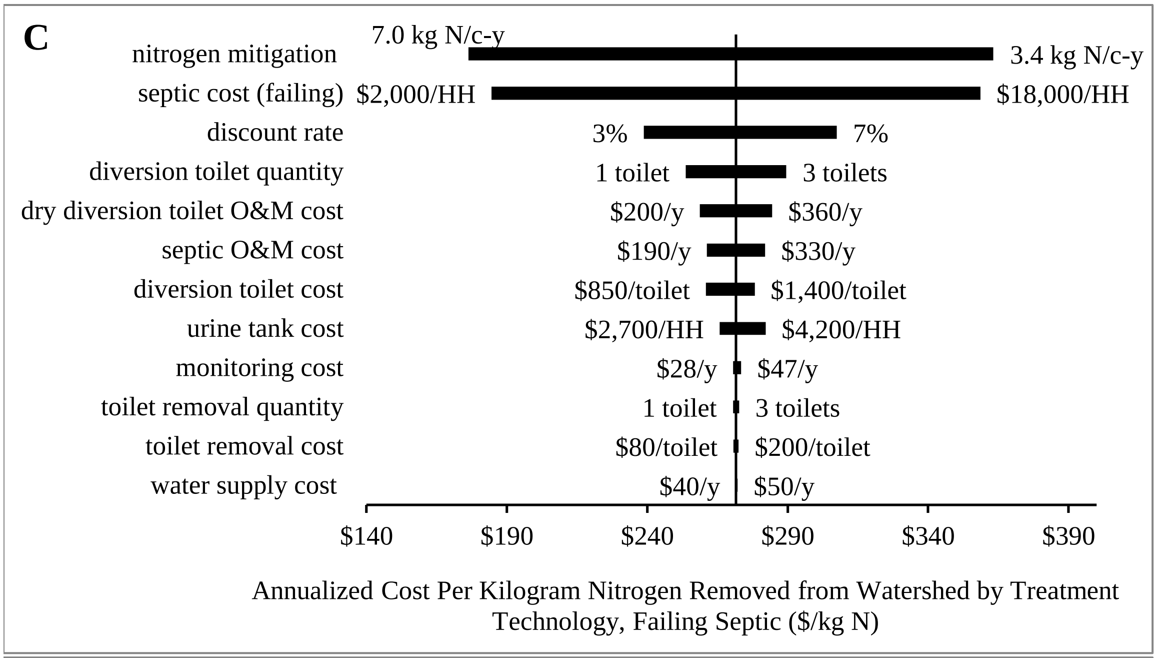


Figure A3. Sensitivity to various factors of cost-effectiveness of flush diversion toilets paired with conventional septic systems for (A) new construction, (B) retrofits of existing homes with usable existing septic, (C) retrofits of existing homes with failing existing septic, and (D) retrofits of homes throughout the town assuming 20% have failing existing septic.


A
nitrogen removal
7.0 kg N/c-y
3.4 kg N/c-y
discount rate
3%
7%
septic cost
$8,000/HH
$13,000/HH
diversion toilet quantity
1 toilet
3 toilets
dry diversion toilet O&M cost
$200/y
$360/y
septic O&M cost
$190/y
$330/y
diversion toilet cost
$850/toilet
$1,500/toilet
urine tank cost
$2,700/HH
$4,200/HH
monitoring cost
$28/y
$47/y
water supply cost
$40/y
$50/y
$140 $170 $200 $230 $260 $290 $320 $350 $380
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology ($/kg N)
B
nitrogen mitigation
7.0 kg N/c-y
3.4 kg N/c-y
septic cost (usable)
$0/HH
$9,000/HH
discount rate
3%
7%
diversion toilet quantity
1 toilet
3 toilets
dry diversion toilet O&M cost
$200/y
$360/y
septic O&M cost
$190/y
$330/y
diversion toilet cost
$850/toilet
$1,400/toilet
urine tank cost
$2,700/HH
$4,200/HH
monitoring cost
$28/y
$47/y
toilet removal quantity
1 toilet
3 toilets
toilet removal cost
$80/toilet
$200/toilet
water supply cost
$40/y
$50/y
$100 $120 $140 $160 $180 $200 $220 $240 $260 $280 $300 $320
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology, Usable Septic ($/kg N)



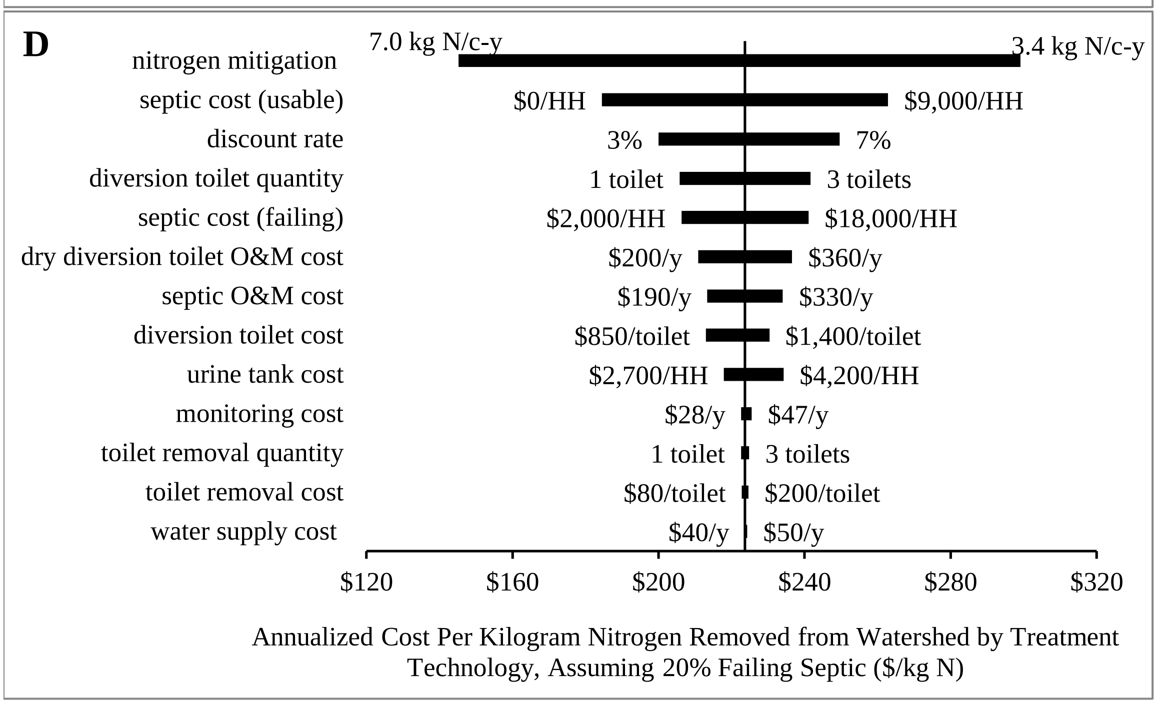
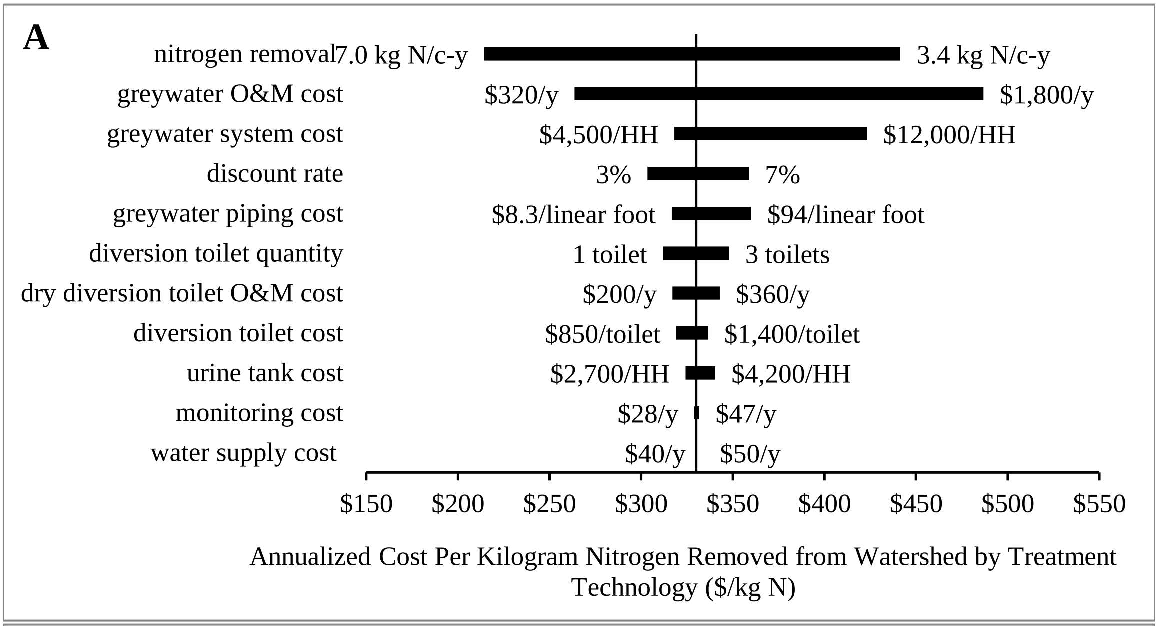


Figure A4. Sensitivity to various factors of cost-effectiveness of dry diversion toilets paired with conventional septic systems for (A) new construction, (B) retrofits of existing homes with usable existing septic, (C) retrofits of existing homes with failing existing septic, and (D) retrofits of homes throughout the town assuming 20% have failing existing septic.



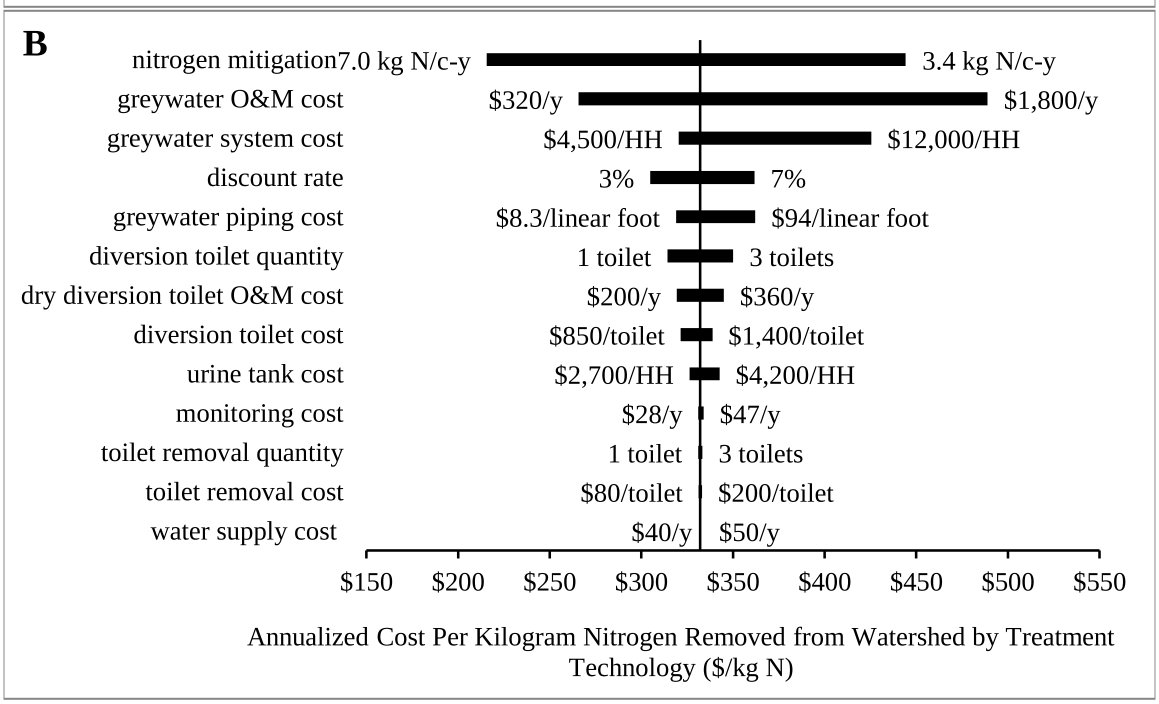
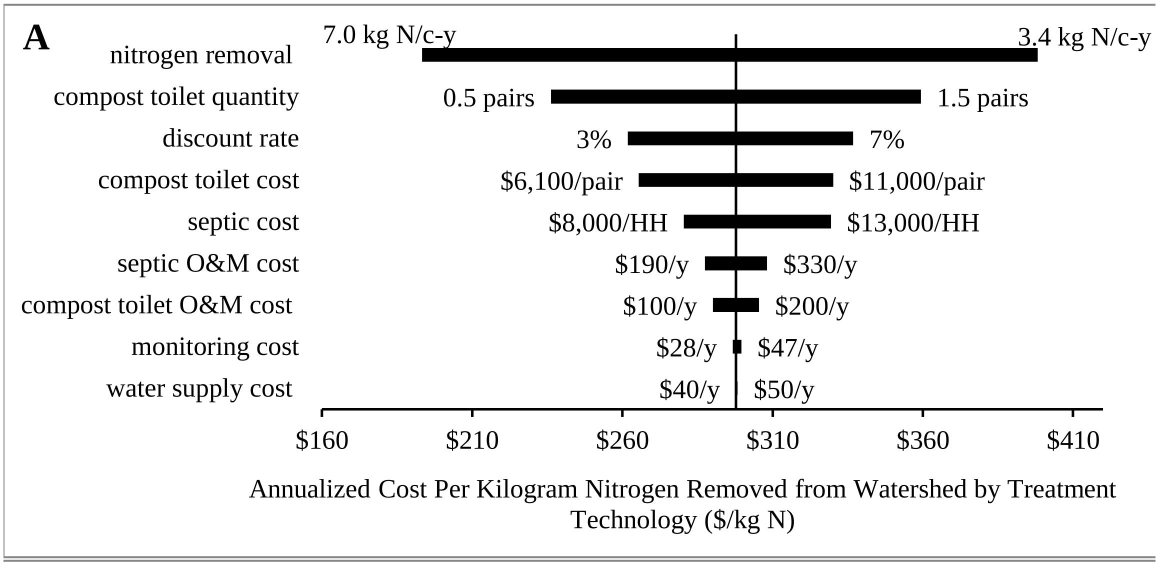
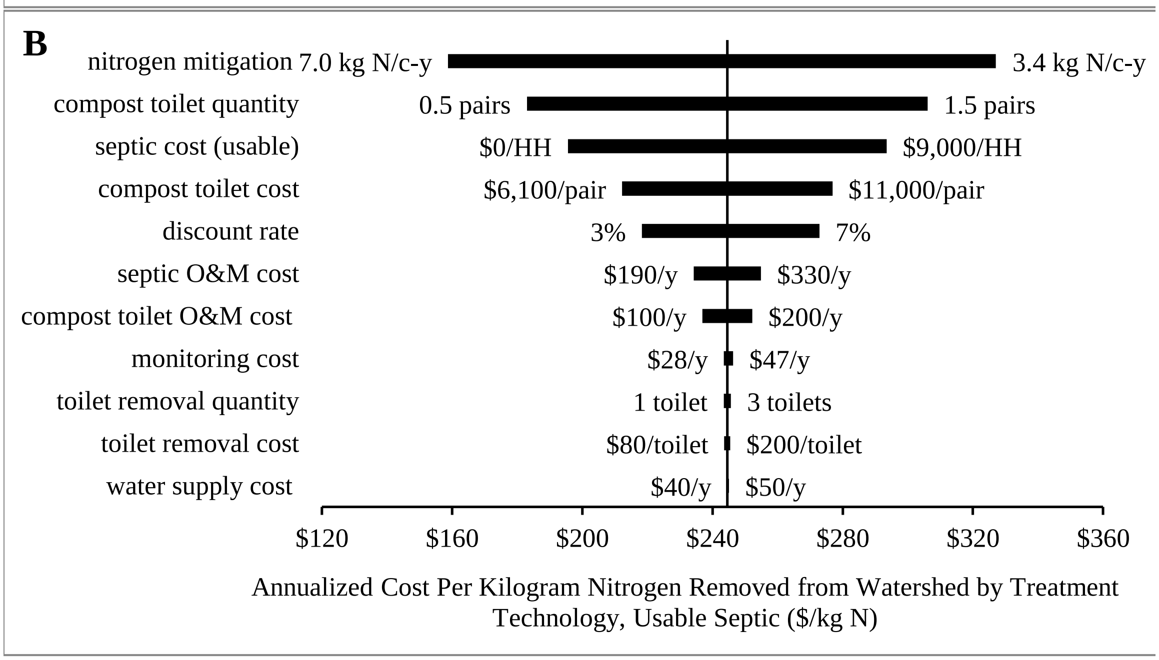


Figure A5. Sensitivity to various factors of cost-effectiveness of dry diversion toilets paired with greywater recycling for (A) new construction, and (B) retrofits of existing homes.


A
nitrogen removal
7.0 kg N/c-y
3.4 kg N/c-y
compost toilet quantity
0.5 pairs
1.5 pairs
discount rate
3%
7%
compost toilet cost
$6,100/pair
$11,000/pair
septic cost
$8,000/HH
$13,000/HH
septic O&M cost
$190/y
$330/y
compost toilet O&M cost
$100/y
$200/y
monitoring cost
$28/y
$47/y
water supply cost
$40/y
$50/y
$160
$210
$260
$310
$360
$410
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology ($/kg N)


B
nitrogen mitigation
7.0 kg N/c-y
3.4 kg N/c-y
compost toilet quantity
0.5 pairs
1.5 pairs
septic cost (usable)
$0/HH
$9,000/HH
compost toilet cost
$6,100/pair
$11,000/pair
discount rate
3%
7%
septic O&M cost
$190/y
$330/y
compost toilet O&M cost
$100/y
$200/y
monitoring cost
$28/y
$47/y
toilet removal quantity
1 toilet
3 toilets
toilet removal cost
$80/toilet
$200/toilet
water supply cost
$40/y
$50/y
$120
$160
$200
$240
$280
$320
$360
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology, Usable Septic ($/kg N)

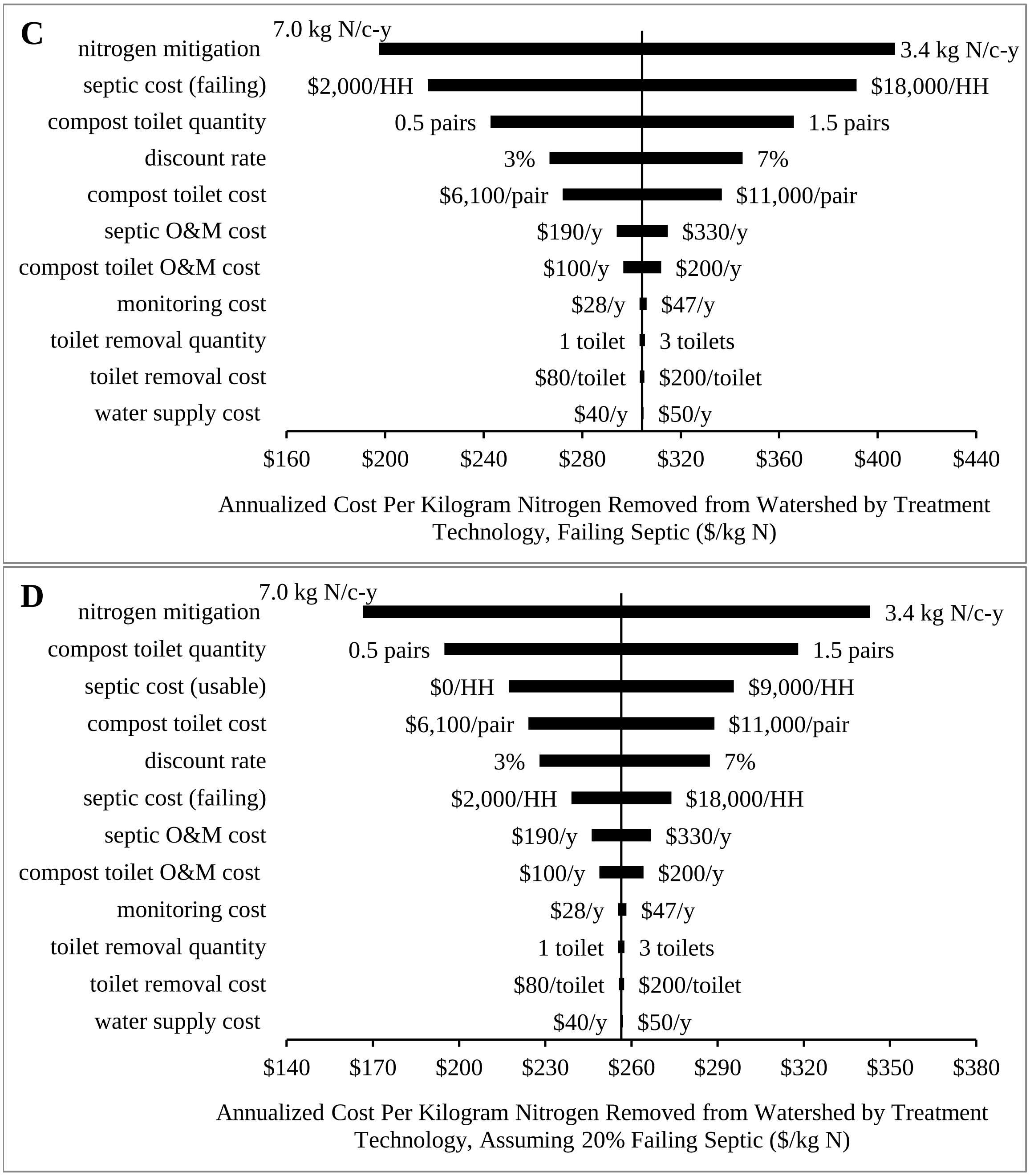


Figure A6. Sensitivity to various factors of cost-effectiveness of composting toilets paired with conventional septic systems for (A) new construction, (B) retrofits of existing homes with usable existing septic, (C) retrofits of existing homes with failing existing septic, and (D) retrofits of homes throughout the town assuming 20% have failing existing septic.

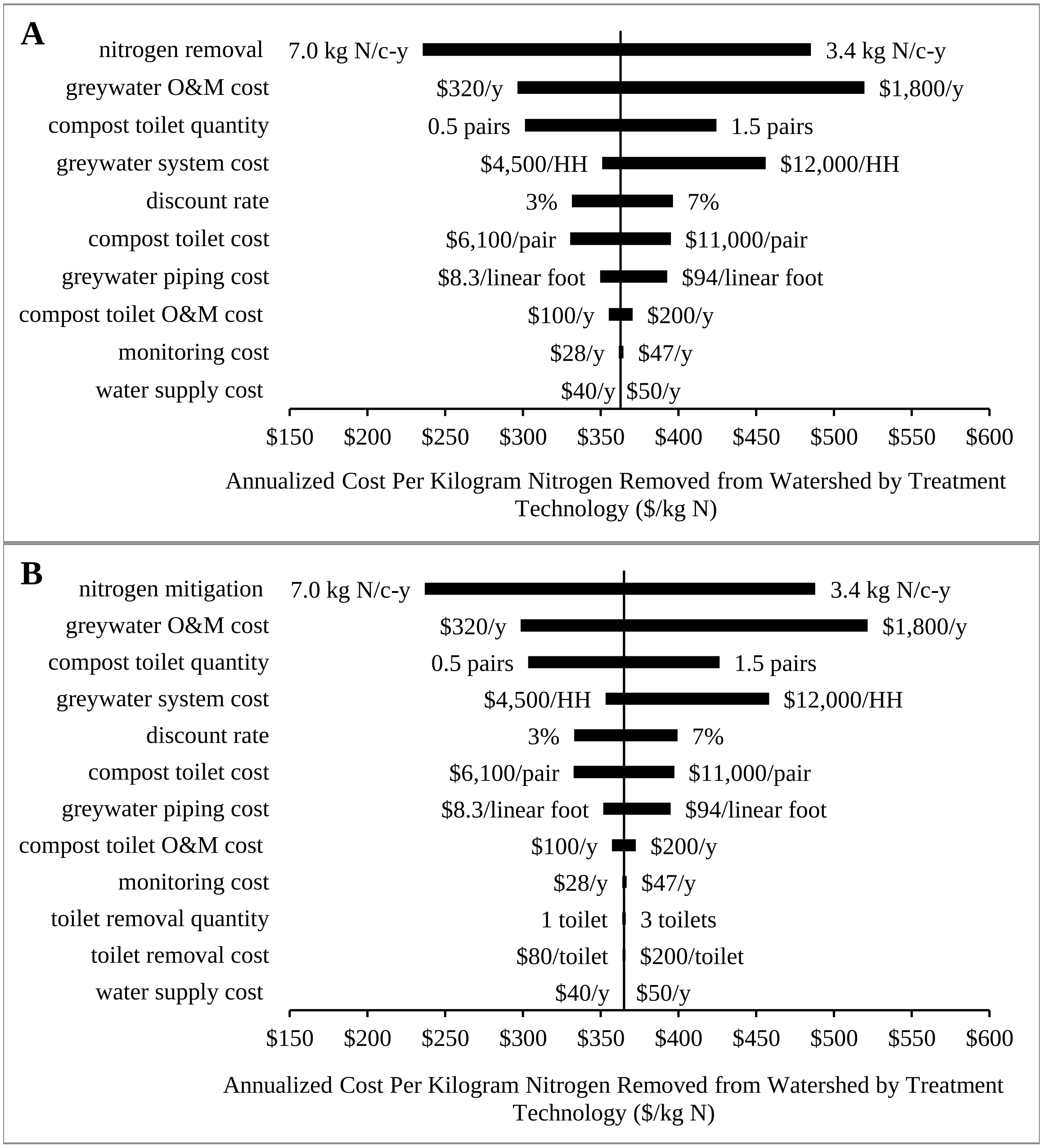
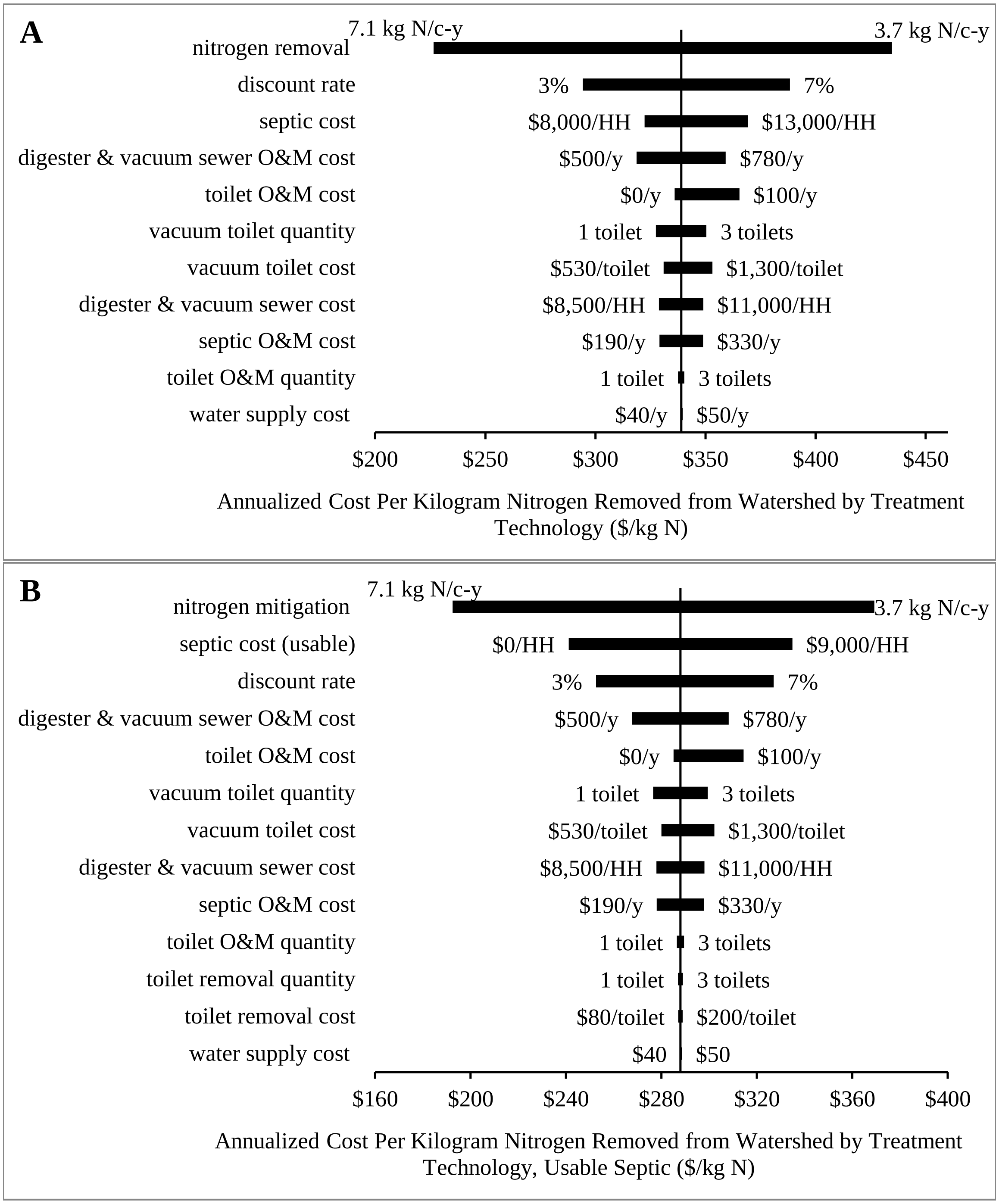
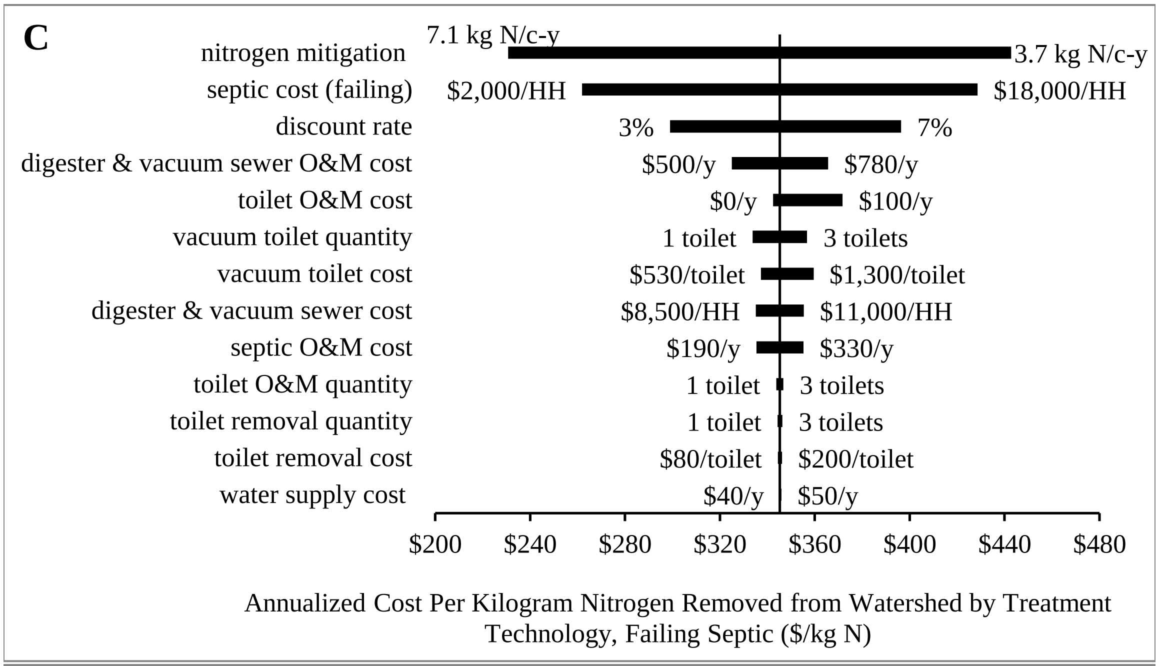


Figure A7. Sensitivity to various factors of cost-effectiveness of composting toilets paired with greywater recycling for (A) new construction, and (B) retrofits of existing homes.


A
nitrogen removal
7.1 kg N/c-y
3.7 kg N/c-y
discount rate
3%
7%
septic cost
$8,000/HH
$13,000/HH
digester & vacuum sewer O&M cost
$500/y
$780/y
toilet O&M cost
$0/y
$100/y
vacuum toilet quantity
1 toilet
3 toilets
vacuum toilet cost
$530/toilet
$1,300/toilet
digester & vacuum sewer cost
$8,500/HH
$11,000/HH
septic O&M cost
$190/y
$330/y
toilet O&M quantity
1 toilet
3 toilets
water supply cost
$40/y
$50/y
$200
$250
$300
$350
$400
$450
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology ($/kg N)
B
nitrogen mitigation
7.1 kg N/c-y
3.7 kg N/c-y
septic cost (usable)
$0/HH
$9,000/HH
discount rate
3%
7%
digester & vacuum sewer O&M cost
$500/y
$780/y
toilet O&M cost
$0/y
$100/y
vacuum toilet quantity
1 toilet
3 toilets
vacuum toilet cost
$530/toilet
$1,300/toilet
digester & vacuum sewer cost
$8,500/HH
$11,000/HH
septic O&M cost
$190/y
$330/y
toilet O&M quantity
1 toilet
3 toilets
toilet removal quantity
1 toilet
3 toilets
toilet removal cost
$80/toilet
$200/toilet
water supply cost
$40
$50
$160
$200
$240
$280
$320
$360
$400
Annualized Cost Per Kilogram Nitrogen Removed from Watershed by Treatment Technology, Usable Septic ($/kg N)



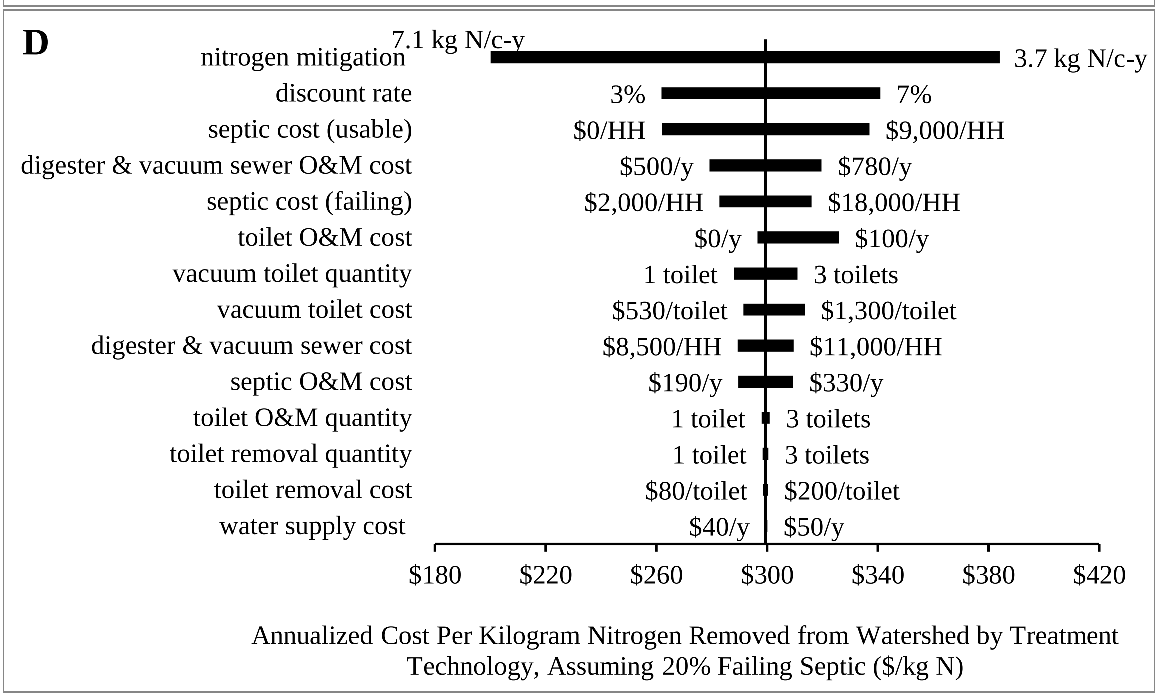


Figure A8. Sensitivity to various factors of cost-effectiveness of blackwater digesters paired with conventional septic systems for (A) new construction, (B) retrofits of existing homes with usable existing septic, (C) retrofits of existing homes with failing existing septic, and (D) retrofits of homes throughout the town assuming 20% have failing existing septic.

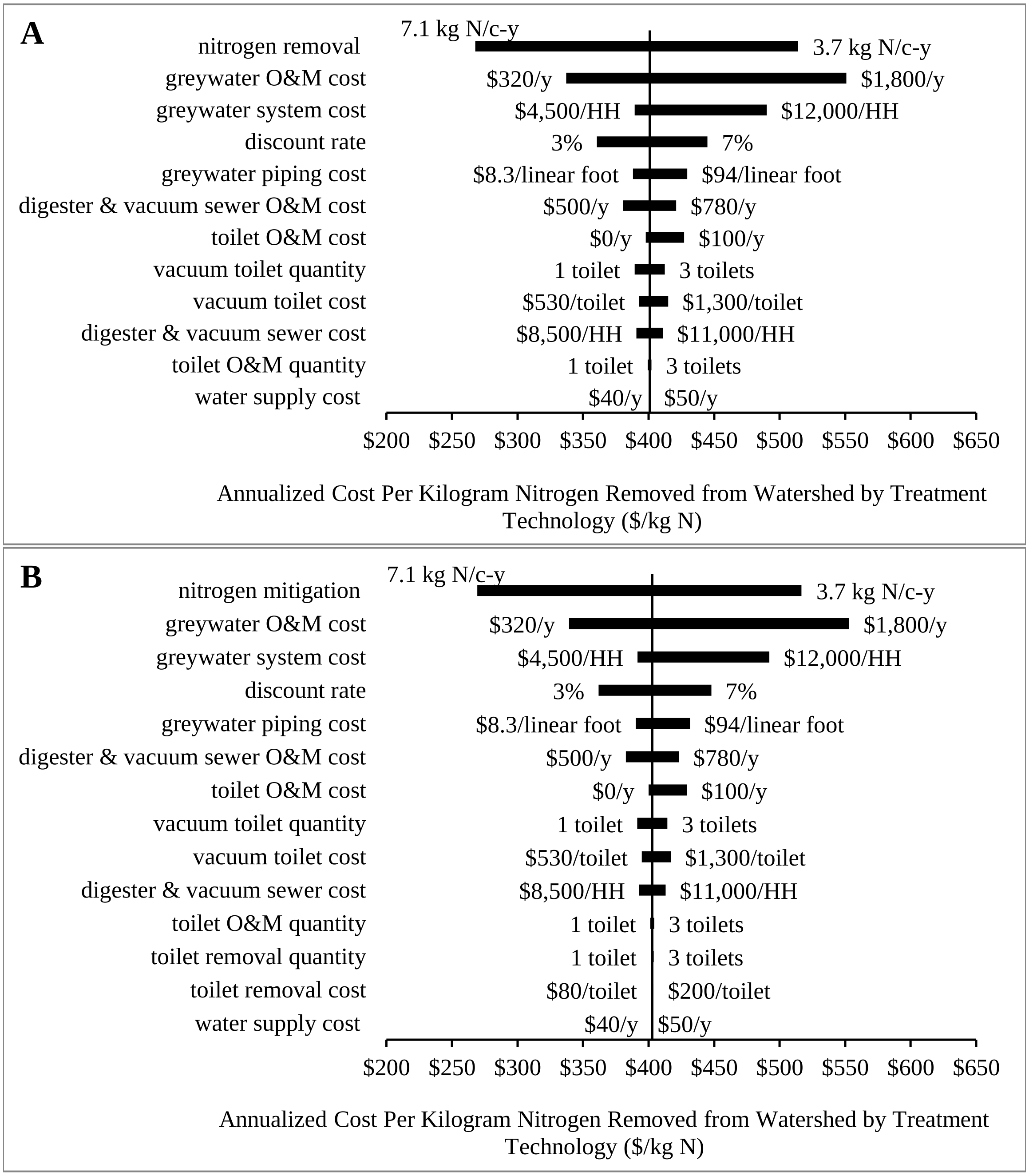


Figure A9. Sensitivity to various factors of cost-effectiveness of blackwater digesters paired with conventional septic systems for (A) new construction, and (B) retrofits of existing homes.

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Appendix B: Supporting Information for Chapter 4[6]

ALCOSAN Case Study Cost Data

Table B1 summarizes the sources and assumptions used in life cycle cost estimates for the ALCOSAN service area case study. Whenever possible, cost estimates were obtained directly from vendors and service providers in the ALCOSAN service area.

Table B1 Cost data, sources, and assumptions used in the cost and cost-effectiveness analyses

Cost Item	Capital Cost (low / base / high)	Capital Cost References	Annual O&M Cost (low / base / high)	O&M Cost References	Notes and Assumptions
WWTP and gravity sewers	--	--	$260 / $440 / $688 no upgrades $633 / $813 / $1,061 with upgrades	ALCOSAN Wet Weather Plan[1]	Wet Weather Plan only includes wastewater rates for collecting operation and maintenance funds for the existing system, with or without upgrades.
I/A septic systems	$11,000 / $20,000 / $30,000	Personal communication with vendors and service providers[2-5]	$362 / $519 / $640	Personal communication with vendors and service providers, compiled data from providers[2,5-7]	Includes costs for Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics.
standard toilet	$356 / $523 / $688	RS Means[8]	$0 / $10 / $100	assumed	Includes multiple mounting options. O&M assumes one $100 servicing every 10 years for base case, annual $100 servicing for high case, no maintenance for low case.

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Table B1, continued

urine-diversion toilet	$822 / $1,186 / $1,412 toilet $1,333 / $1,433 / $1,533 tank	Personal communication with vendors and service providers, published data from vendors, RS Means [8-13]	$130 / $158 / $200 flush $198 / $269 / $350 dry	Personal communication with vendor/service provider,[14] assumed	Includes dry and flush toilet options. Installation costs are 'bare labor.' Assumes 500-gallon urine tank (⅓ of standard septic tank), located outdoors. Flush toilet O&M is ⅔ of septic O&M cost, assuming some fixed costs. Dry toilet O&M comes from flush toilet O&M and compost toilet O&M.
compost toilet	$6,118 / $8,308 / $10,498	Personal communication with manufacturer, RS Means[15,8]	$100 / $150 / $200	Personal communication with manufacturer and vendor[16,17]	Includes dry toilet and foam flush options, two sizes of composter. Installation costs are 'bare labor.' Capital costs are for a pair of toilets with one compost container.
blackwater digesters and pressure or vacuum sewers	$8,450 / $9,710 / $10,960	Literature[18]	$500 / $640 / $780	Literature[18]	Euros converted to USD at €1 to $1.37. Includes pressure and vacuum sewer network options.
vacuum toilet	$500 / $790 / $1320	Personal communication with vendors, published data from vendors, literature[18-22]	$0 / $10 / $100	assumed	Euros converted to USD at €1 to $1.37. Installation is 'bare labor.' O&M assumed same as standard toilet.
variable drinking water supply cost	--	--	$87 / $270 / $752	Personal communication with service providers, published data from services providers, American Community Survey[23-32]	Weighted average of water rates from suppliers to towns within ALCOSAN service area, weighted by population. Water consumption based on average household size for towns within ALCOSAN service area.
decentralized monitoring	--	--	$14 / $18 / $24	American Community Survey,[32] assumed	Assumes $35,500 per year for one inspector based on median income in ALCSOAN service area, 6-10 inspections per day, working 250 days/year.
removal of existing standard toilet	$66 / $110 / $150	Personal communication with service providers [33,34]	--	--	--

LIFE CYCLE COST ESTIMATE SENSITIVITY ANALYSIS

Figures B1 – B6 show cost sensitivity analysis for the systems analyzed for the Falmouth, Massachusetts case study. These tornado diagrams show one-way sensitivity. The tornado is centered on the total system NPV when all parameters are at their base case values; each bar shows the range of total system NPV as one parameter varies between the endpoints shown (with base case values in parentheses). Thus these diagrams show both the results of the life cycle cost modeling and the sensitivity of that cost to variation in the parameters. Cost factors are all on a per-household basis. Municipal discount rate and homeowner loan rate both reflect ranges appropriate for market-based discount rates. Individual discount rate reflects a range appropriate for individual discount rate values, with a base case value of 28% based on an estimated median individual rate for Falmouth and a high case value of 100% based on values from energy efficiency literature being mostly between 10% and 100%. Both retrofit and new construction cases are shown.

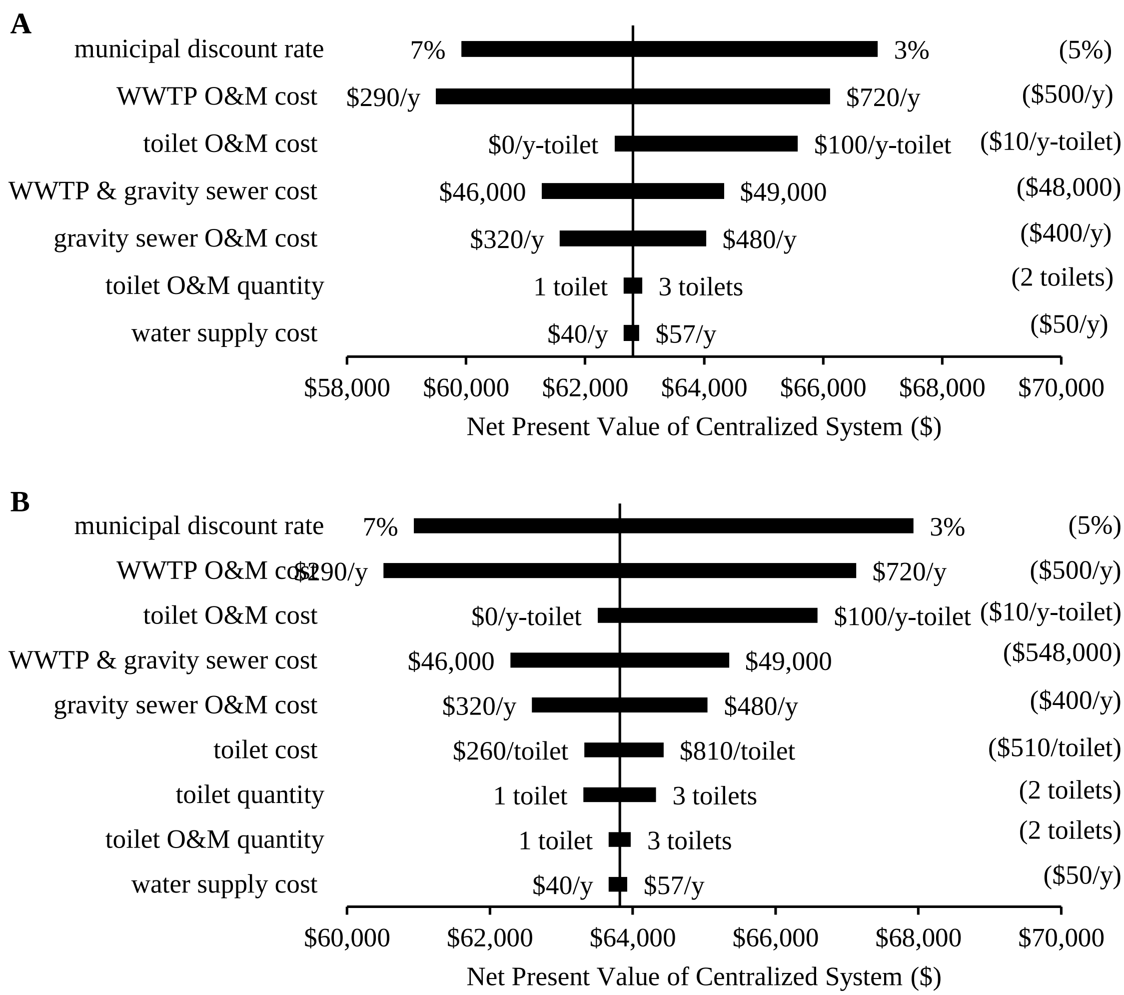


Figure B1. Sensitivity to parameters of net present value of centralized system, for (A) retrofit of existing homes, (B) new construction, Falmouth, Massachusetts case study.

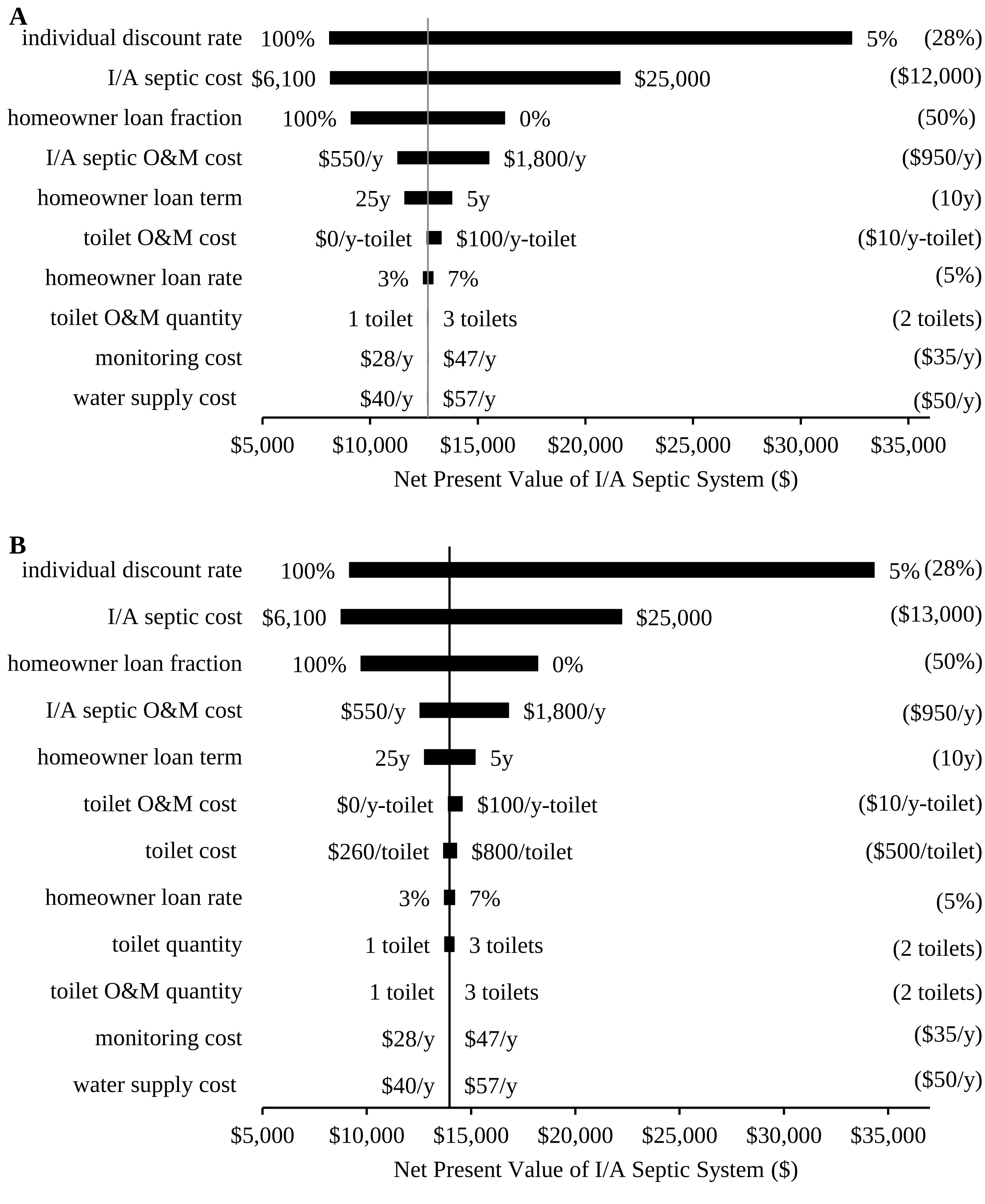


Figure B2. Sensitivity to parameters of net present value of innovative/advanced septic system, for (A) retrofit of existing homes, (B) new construction, Falmouth, Massachusetts case study.

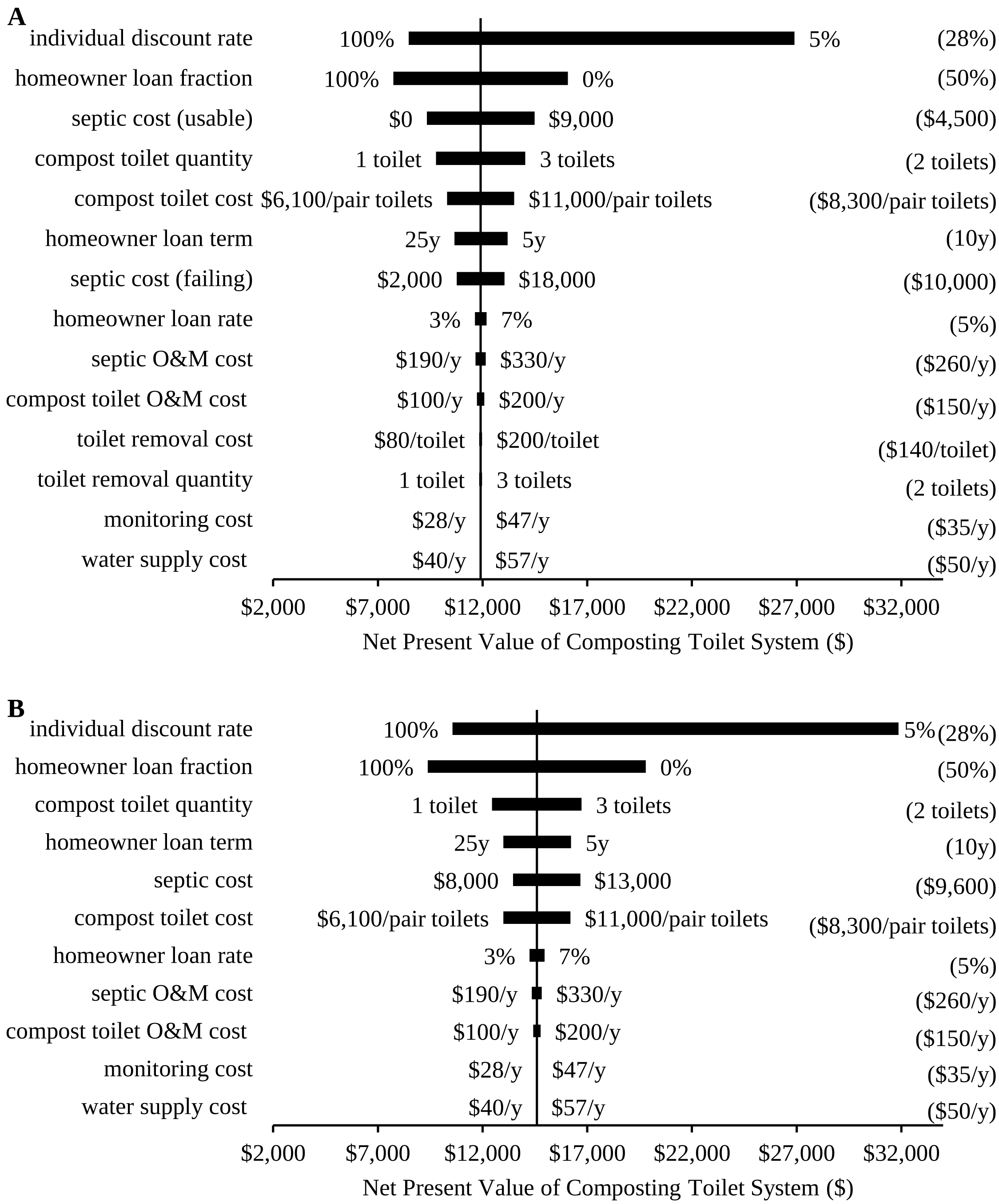


Figure B3. Sensitivity to parameters of net present value of composting toilet system, for (A) retrofit of existing homes, (B) new construction, Falmouth, Massachusetts case study.

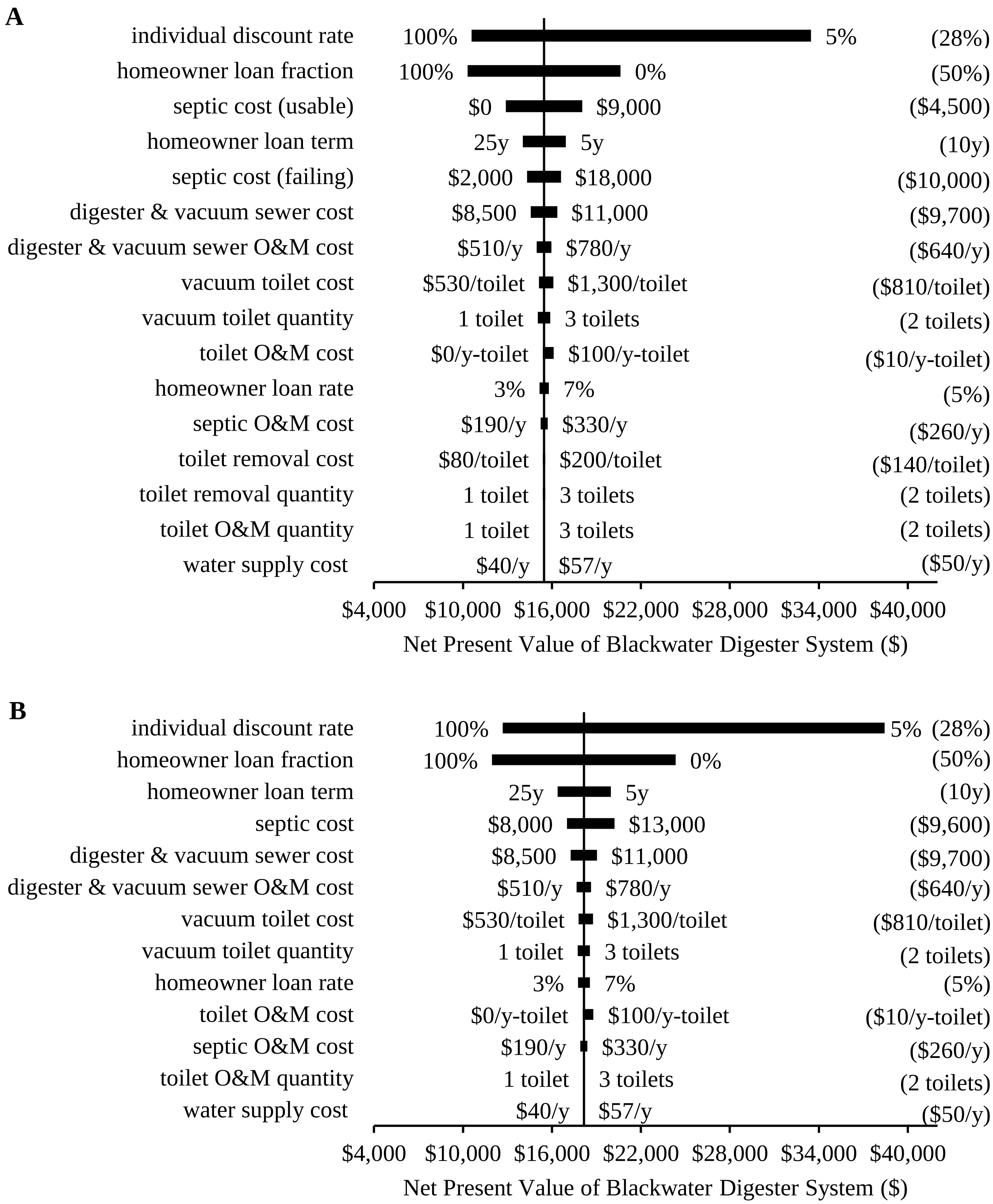


Figure B4. Sensitivity to parameters of net present value of blackwater digester system, for (A) retrofit of existing homes, (B) new construction, Falmouth, Massachusetts case study.

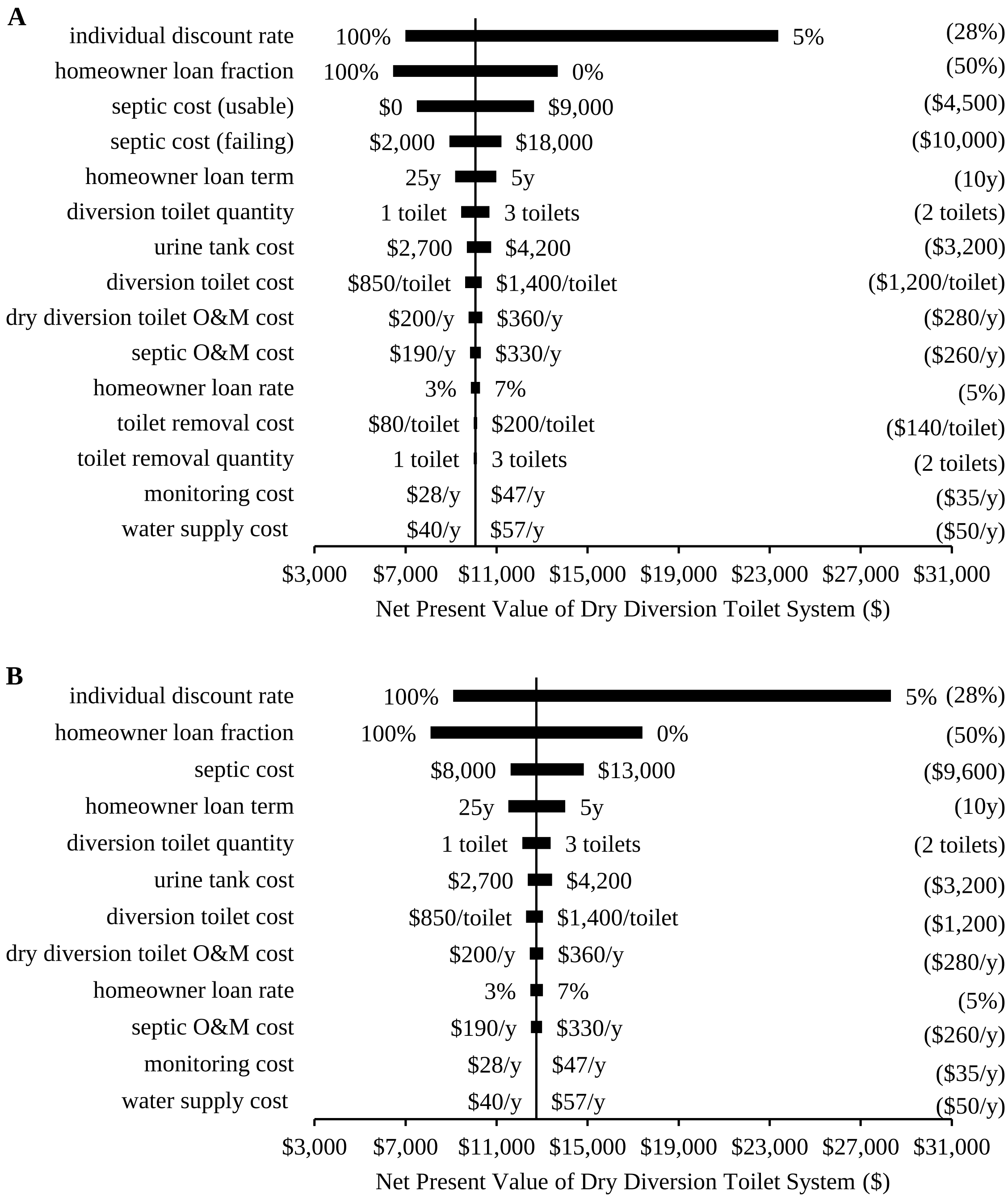


Figure B5. Sensitivity to parameters of net present value of dry (composting) urine-diversion toilet system, for (A) retrofit of existing homes, (B) new construction, Falmouth, Massachusetts case study.

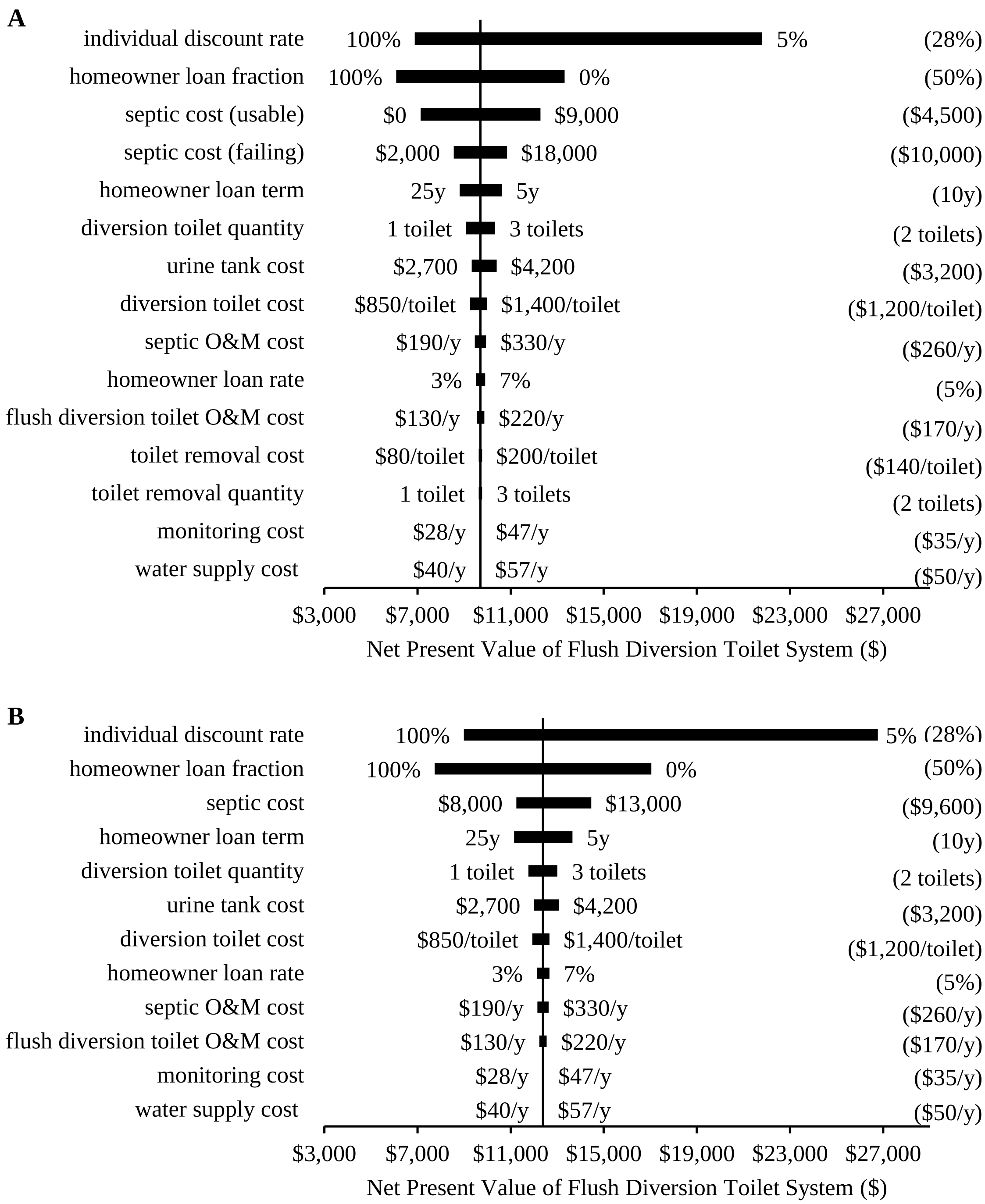


Figure B6. Sensitivity to parameters of net present value of flush urine-diversion toilet system, for (A) retrofit of existing homes, (B) new construction, Falmouth, Massachusetts case study.

Figures B7-B13 show cost sensitivity analysis for the systems analyzed for the ALCOSAN service area case study. These tornado diagrams show one-way sensitivity. The tornado is centered on the total system NPV when all parameters are at their base case values; each bar shows the range of total system NPV as one parameter varies between the endpoints shown (with base case values in parentheses). Thus these diagrams show both the results of the life cycle cost modeling and the sensitivity of that cost to variation in the parameters. Cost factors are all on a per-household basis. Municipal discount rate and homeowner loan rate both reflect ranges appropriate for market-based discount rates. Individual discount rate reflects a range appropriate for individual discount rate values, with a base case value of 37% based on an estimated median individual rate for the ALCOSAN service area and a high case value of 100% based on values from energy efficiency literature being mostly between 10% and 100%. Both retrofit and new construction cases are shown. Note that the flush diversion system is included here for completeness, as system cost information might be useful to readers.

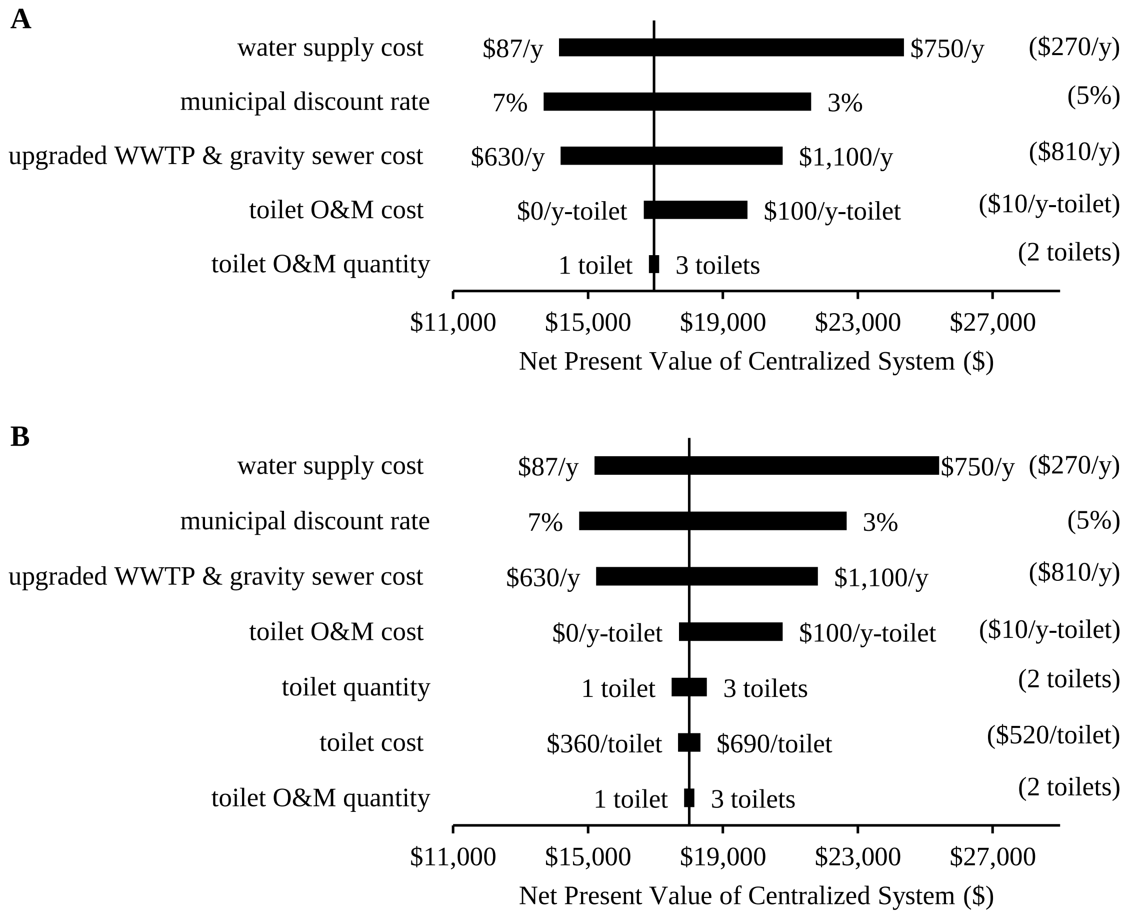


Figure B7. Sensitivity to parameters of net present value of centralized system, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.

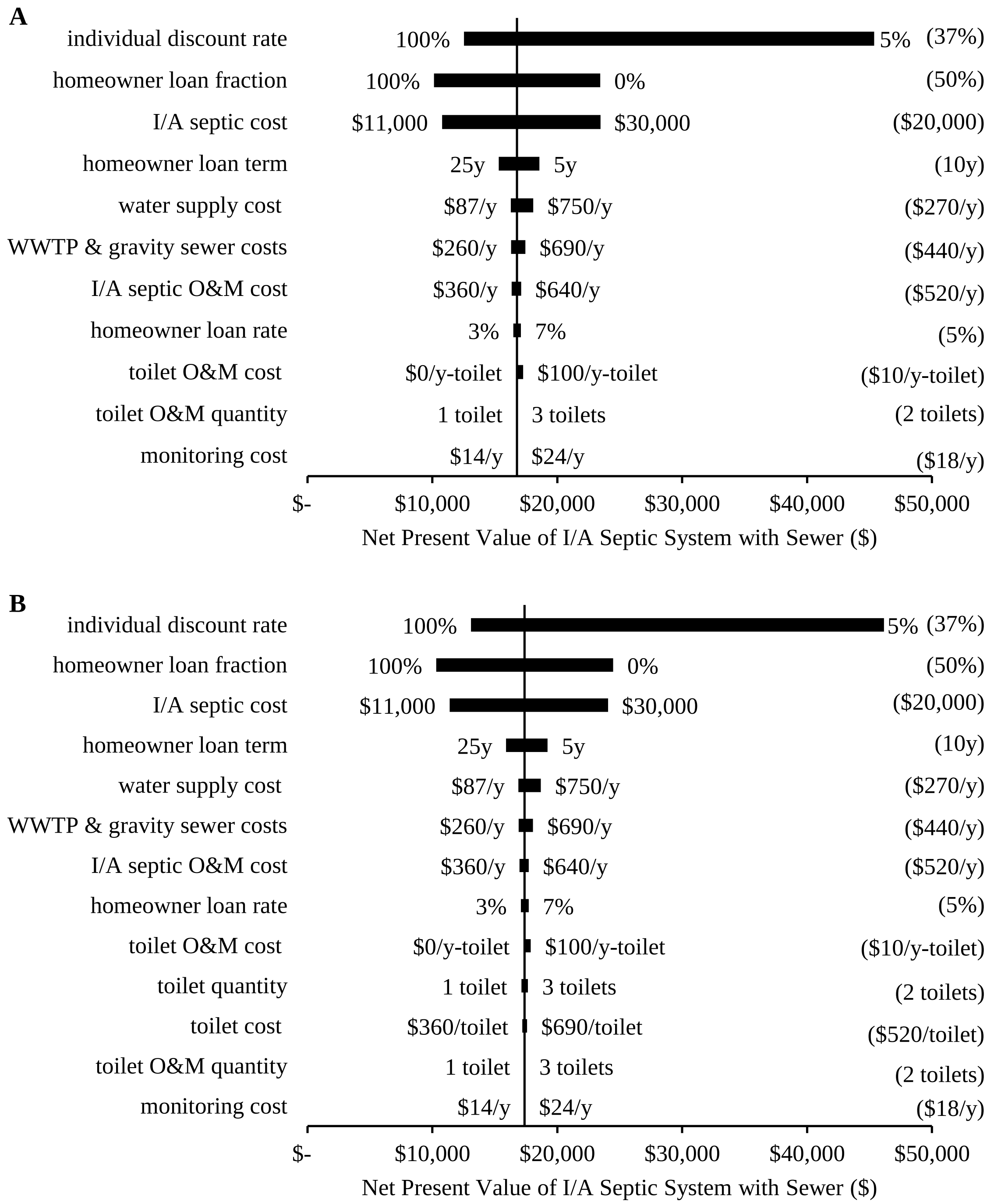
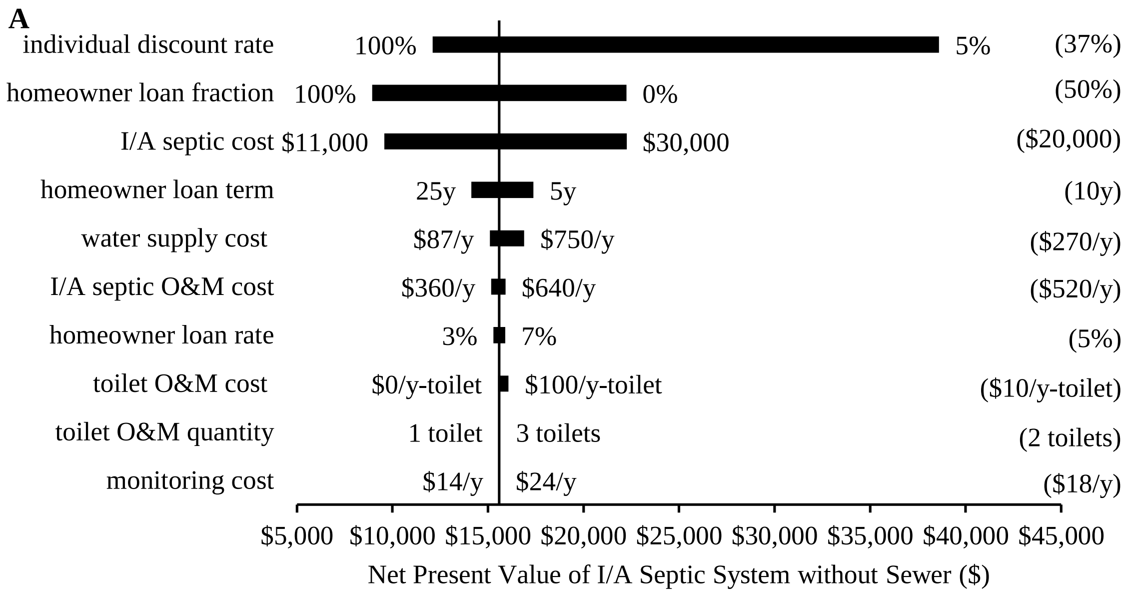


Figure B8. Sensitivity to parameters of net present value of innovative/advanced septic system with payments for sewer connection included, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.



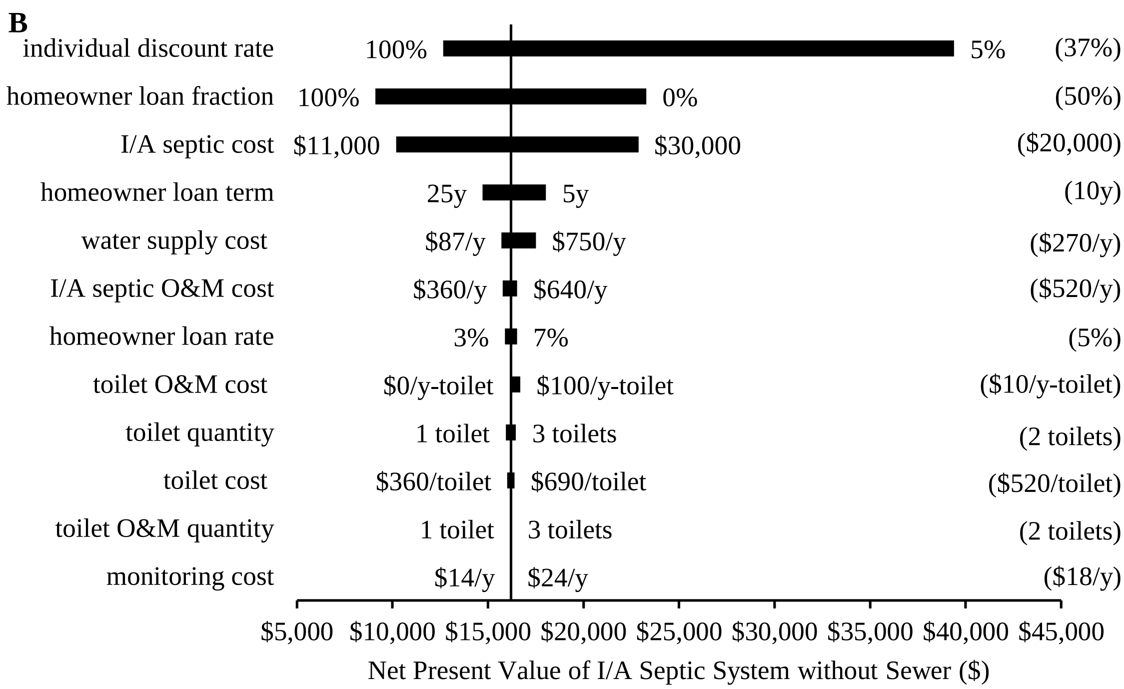


Figure B9. Sensitivity to parameters of net present value of innovative/advanced septic system without payment for sewer connection included, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.

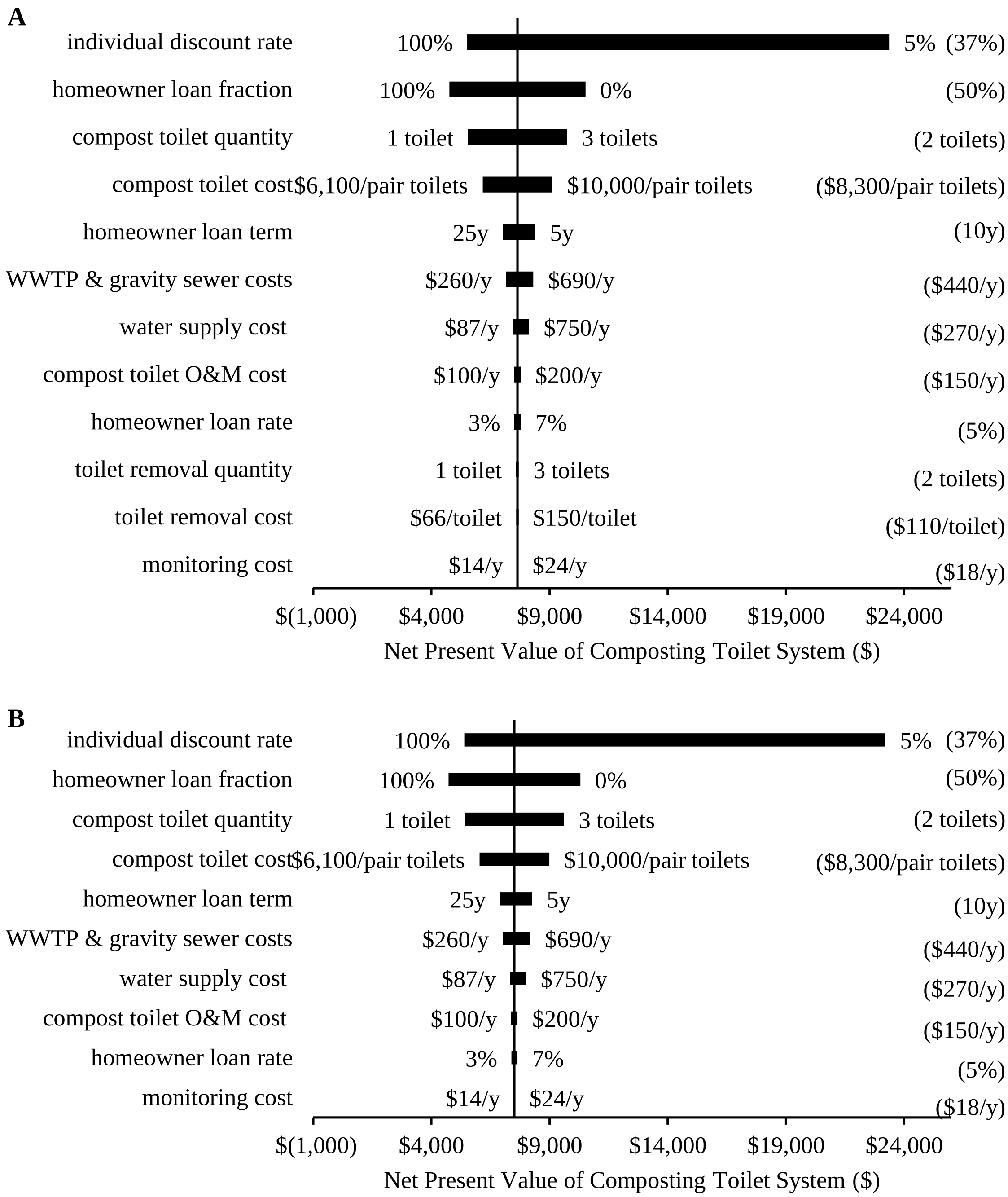


Figure B10. Sensitivity to parameters of net present value of composting toilet system, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.

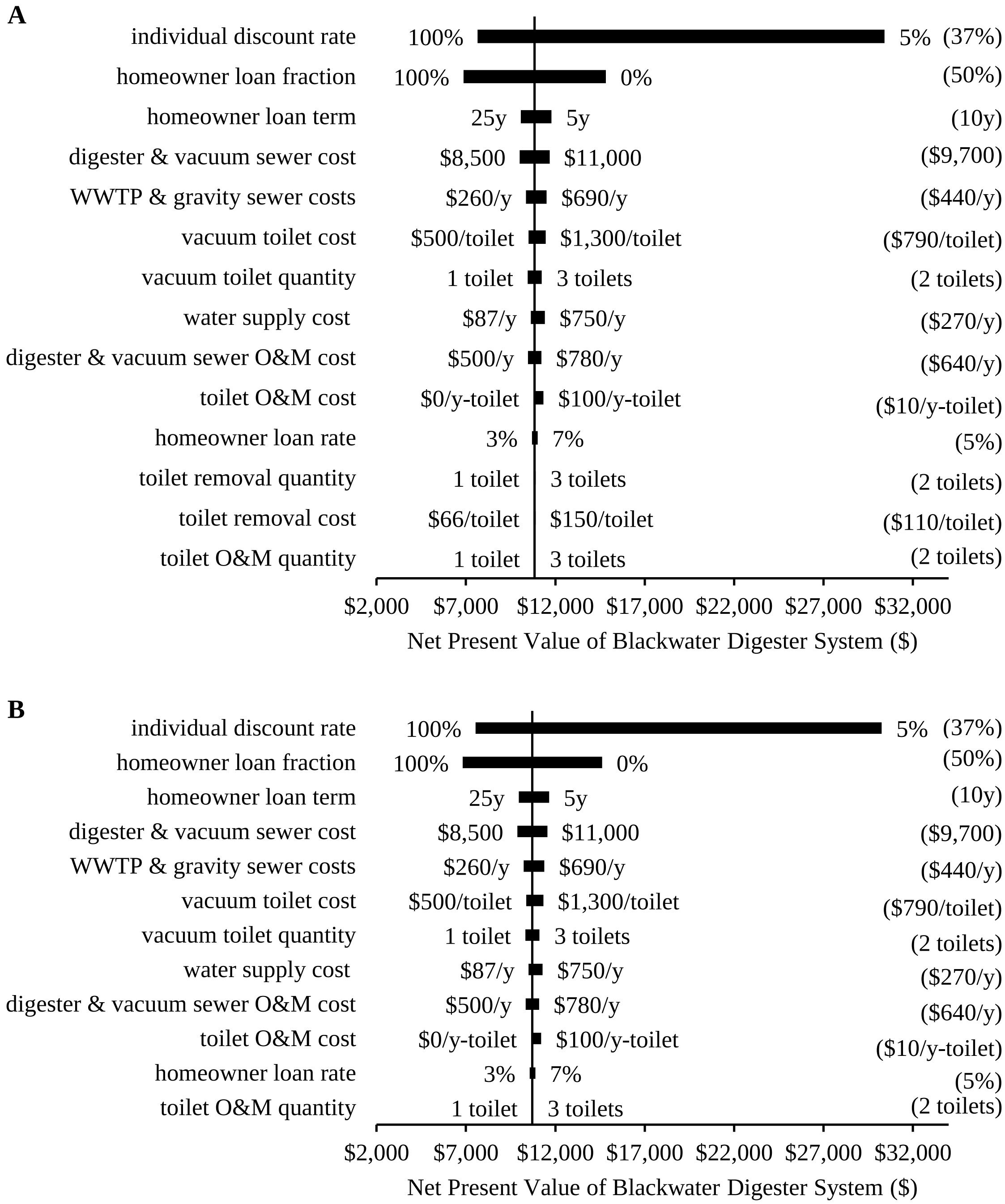


Figure B11. Sensitivity to parameters of net present value of blackwater digester system, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.

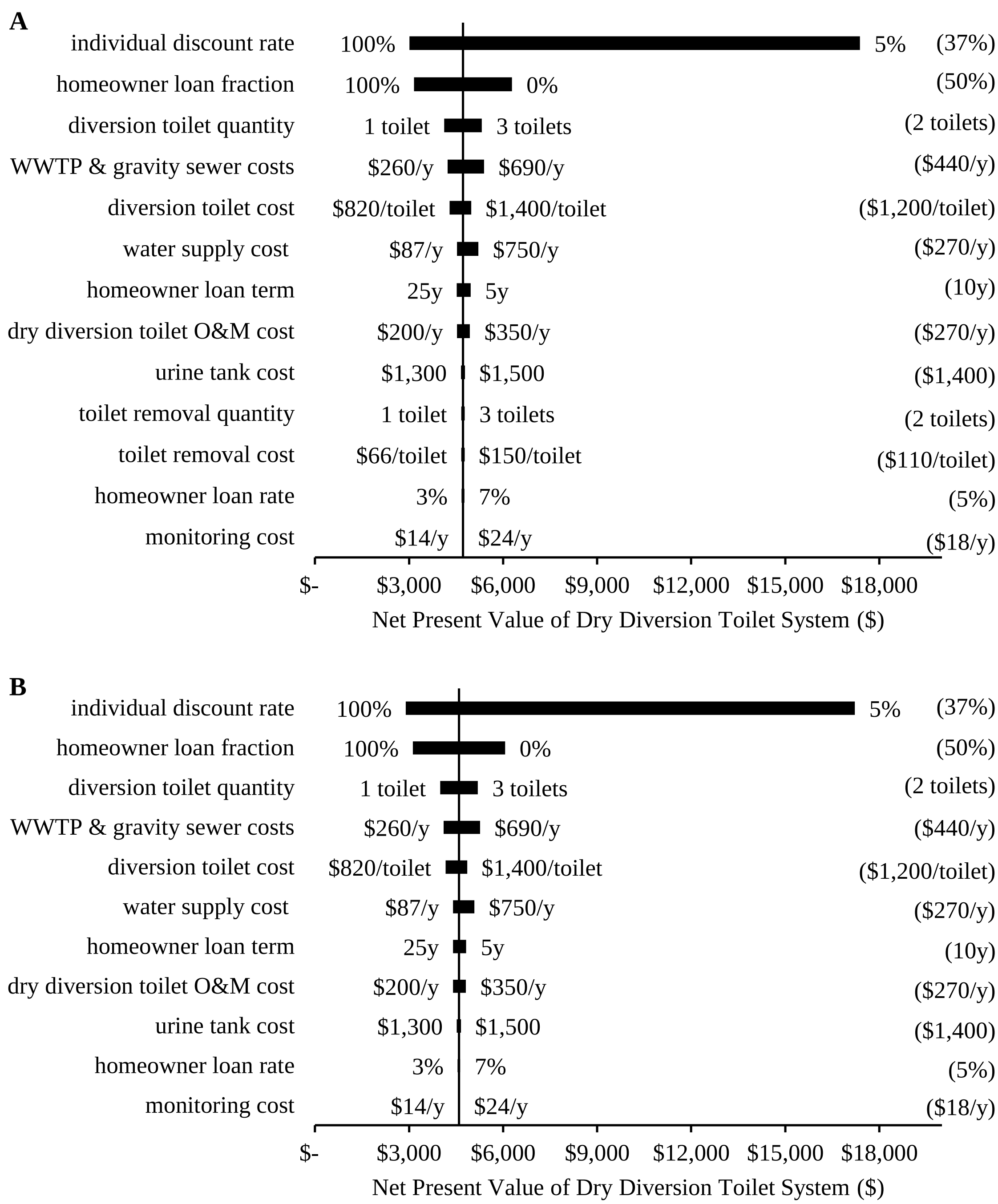
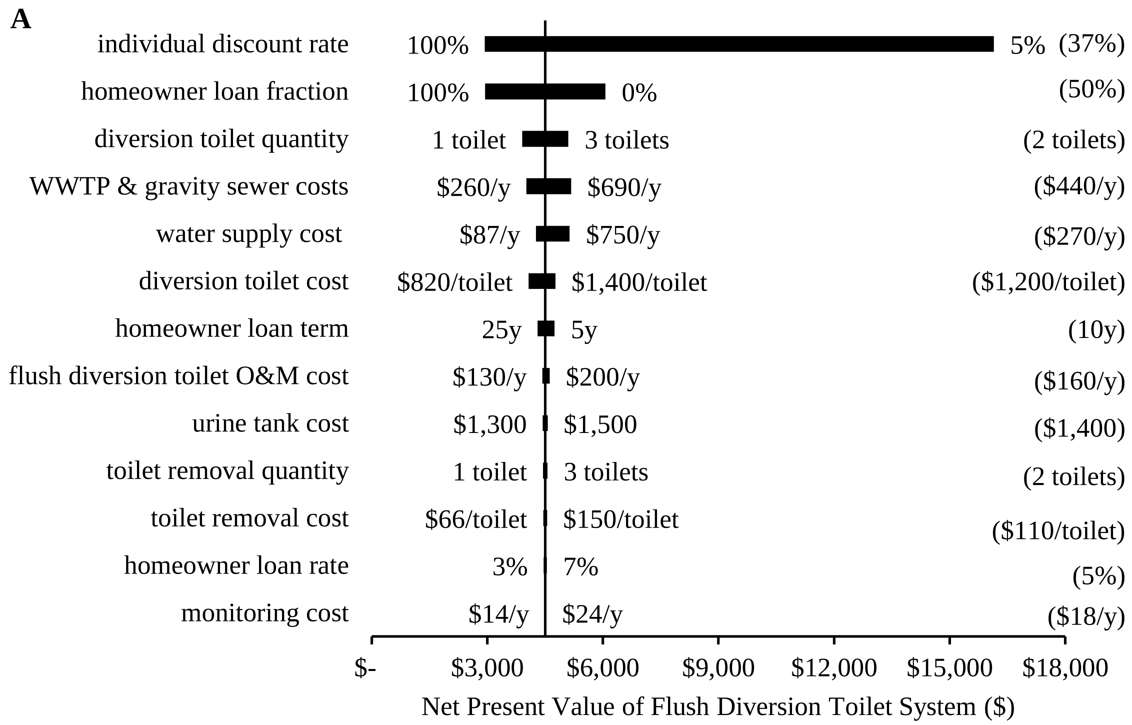


Figure B12. Sensitivity to parameters of net present value of dry (composting) urine-diversion toilet system, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.



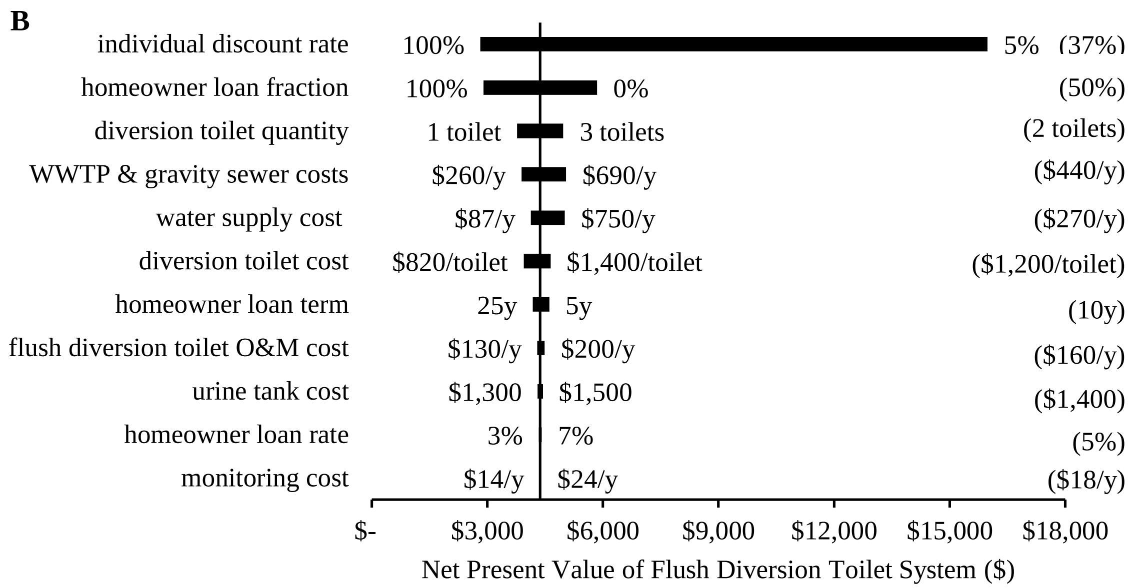


Figure B13. Sensitivity to parameters of net present value of flush urine-diversion toilet system, for (A) retrofit of existing homes, (B) new construction, ALCOSAN service area case study.

EQUATIONS FOR INCENTIVE CASH FLOWS #1 AND #3

The Equations in the paper show only incentive cash flow #2, in which the entire incentive is spread into equal annual payments over 30 years; here are the equations for cash flow #1, in which the entire incentive is paid up front, and #3, in which the entire incentive is split into equal annual payments. Equations SI-1 – SI-4 shown here are identical to Equations 1-4 in the paper, regardless of incentive cash flow: these calculate the NPV from each party's perspective and find the differences between centralized and decentralized system costs.

Cash Flow #1

Eq. 9) $$NPV_{mun} = \sum_{up-front\ components}\left[q(1-z)c + qzc(AF(t_{HH}, i_{loan}))(PVF(L \times 12, {}^{i_{mun}}/_{12})\right] + \sum_{all\ annual\ components}\left[qc\left(PVF(L, i_{mun})\right)\right]$$

Eq. 10) $$NPV_{HH} = \sum_{up-front\ components}\left[q(1-z)c + qzc(AF(t_{HH}, i_{loan}))(PVF(L \times 12, {}^{i_{HH}}/_{12})\right] + \sum_{all\ annual\ components}\left[qc\left(PVF(L, i_{HH})\right)\right]$$

Eq. 11) $$minimum\ incentive\ accepted = NPV_{HH,D} - NPV_{HH,C}$$

Eq. 12) $$maximum\ incentive\ offered = NPV_{mun,C} - NPV_{mun,D}$$

Equations SI-5 and SI-6 reflect the incentive cash flow #1.

Eq. 13) $$incentive\ cash\ flow\ \#1 = (maximum\ incentive\ offered)$$

Eq. 14) $$NPV\ of\ incentive\ cash\ flow\ \#1_{HH} = (incentive\ cash\ flow\ \#1)$$

Equation SI-7 is again identical to Equation 7 in the paper:

Eq. 15) $$NPV\ of\ incentive\ cash\ flow\ \#1_{HH} = minimum\ incentive\ accepted$$

Substitutions again reflect the specific cash flow, so that Equation SI-8 is appropriate for incentive cash flow #1:

Eq. 16) $$\left(NPV_{mun,C} - NPV_{mun,D}\right) = NPV_{HH,D} - NPV_{HH,C}$$

Cash Flow #3

Equations SI-9 – SI-16 are appropriate for incentive cash flow #3. Equations SI-9 – SI-12 shown here are identical to Equations 1-4 in the paper, regardless of incentive cash flow: these calculate the NPV from each party's perspective and find the differences between centralized and decentralized system costs.

Eq. 17) $NPV_{mun} = \sum_{up-front\ components}\left[q(1-z)c + qzc(AF(t_{HH}, i_{loan}))(PVF(L \times 12, {}^{i_{mun}}/_{12})\right] + \sum_{all\ annual\ components}\left[qc\left(PVF(L, i_{mun})\right)\right]$

Eq. 18) $NPV_{HH} = \sum_{up-front\ components}\left[q(1-z)c + qzc(AF(t_{HH}, i_{loan}))(PVF(L \times 12, {}^{i_{HH}}/_{12})\right] + \sum_{all\ annual\ components}\left[qc\left(PVF(L, i_{HH})\right)\right]$

Eq. 19) $minimum\ incentive\ accepted = NPV_{HH,D} - NPV_{HH,C}$

Eq. 20) $maximum\ incentive\ offered = NPV_{mun,C} - NPV_{mun,D}$

Eq. 21) $incentive\ cash\ flow\ \#3 = \frac{1}{2}(maximum\ incentive\ offered) + \frac{1}{2}(maximum\ incentive\ offered)\left(AF(L, i_{mun})\right)$

Eq. 22) $NPV\ of\ incentive\ cash\ flow\ \#3_{HH} = \left(incentive\ cash\ flow\ \#3_{\ up-front\ component}\right) + \left(incentive\ cash\ flow\ \#3_{\ annual\ component}\right)\left(PVF(L, i_{HH})\right)$

Eq. 23) $NPV\ of\ incentive\ cash\ flow\ \#3_{HH} = minimum\ incentive\ accepted$

Eq. 24) $\frac{1}{2}\left(NPV_{mun,C} - NPV_{mun,D}\right) + \frac{1}{2}\left(NPV_{mun,C} - NPV_{mun,D}\right)\left(AF(L, i_{mun})\right)\left(PVF(L, i_{HH})\right) = NPV_{HH,D} - NPV_{HH,C}$

In all equations, the only unknown is the homeowner's individual discount rate i_{HH}, which is solved for. All other values are set according to collected data and necessary assumptions.

ADDITIONAL THRESHOLD ANALYSIS RESULTS

Figures B14 – B16 complement Figure 4.1 in the paper, showing the results of the threshold analysis for additional conditions. Figure B14 shows results for the Falmouth case study when the betterment fees for the centralized system are financed at 2% rather than 0%; Figures B15 and B16 show results for the Falmouth case study (0% betterment interest rate) and the ALCOSAN case study in the case of new construction of homes (excluding the flush diversion system, as it is not relevant). All of these figures are for incentive cash flow #2, when the entire incentive is distributed into equal annual payments over 30 years.

As mentioned in the paper, diversion toilets appear most likely to be viable under the largest number of cost scenarios in both cases. In the Falmouth case, the three remaining systems illustrate the effects of the division of costs between up-front and annual expenses. The I/A septic system costs are fairly evenly split between those paid up front and those paid on an annual basis, and that nearly even split remains for low, base, and high system cost estimates; on the other hand, the composting toilet and digester system expenses are fairly evenly split between up-front and annual costs for the low estimate, but more heavily weighted toward up-front costs for the base scenario estimate, and even more heavily weighted that way for the highest cost estimate. These different relationships between up-front and annual costs explain the different patterns seen in the threshold individual discount rates for these systems: the difference in thresholds between the low, base, and high decentralized cost estimate scenarios is greater for the composting toilet and the digester system than for the I/A septic system.

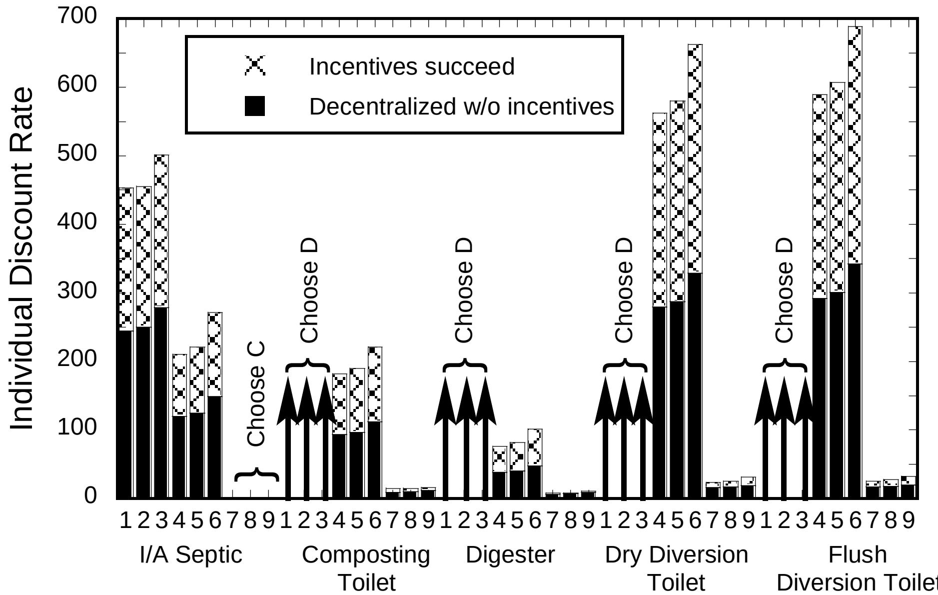


Figure B14. Breakeven points for Falmouth case study, for retrofits of existing homes. Notes: D is decentralized system, C is centralized system. The cost scenarios are denoted by the numerals 1-9: (1) D low cost, C low cost; (2) D low cost, C base cost; (3) D low cost, C high cost; (4) D base cost, C low cost; (5) D base cost, C base cost; (6) D base cost, C high cost; (7) D high cost, C low cost; (8) D high cost, C base cost; (9) D high cost, C high cost. The centralized system cash flow assumes 2% interest for betterment payments. Incentive payment cash flow assumes incentives entirely spread out over time, in equal annual payments

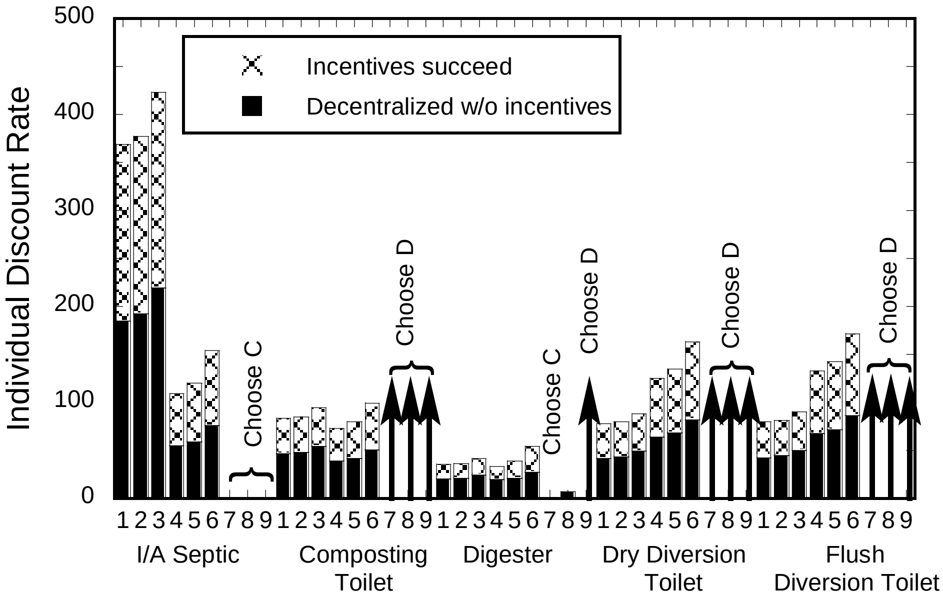


Figure B15. Breakeven points for Falmouth case study, for new home construction. Notes: D is decentralized system, C is centralized system. The cost scenarios are denoted by the numerals 1-9: (1) D low cost, C low cost; (2) D low cost, C base cost; (3) D low cost, C high cost; (4) D base cost, C low cost; (5) D base cost, C base cost; (6) D base cost, C high cost; (7) D high cost, C low cost; (8) D high cost, C base cost; (9) D high cost, C high cost. The centralized system cash flow assumes 0% interest for betterment payments. Incentive payment cash flow assumes incentives entirely spread out over time, in equal annual payments

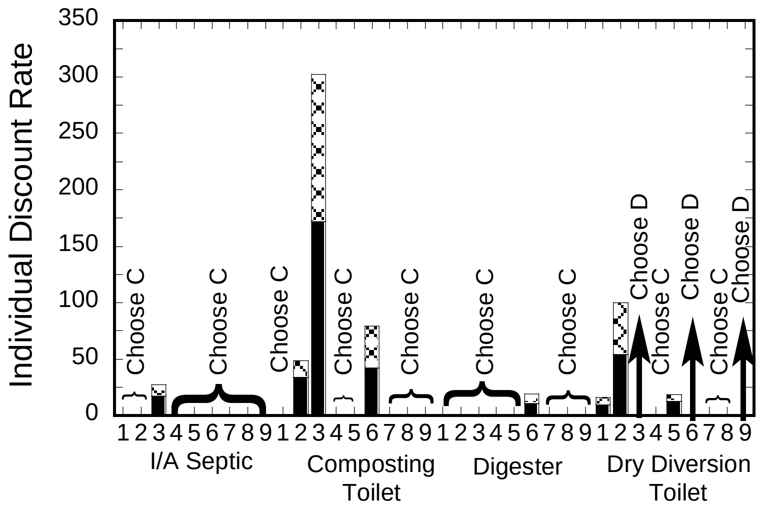


Figure B16. Breakeven points for ALCOSAN service area case study, for new home construction.

Notes: D is decentralized system, C is centralized system. The cost scenarios are denoted by the numerals 1-9: (1) D low cost, C low cost; (2) D low cost, C base cost; (3) D low cost, C high cost; (4) D base cost, C low cost; (5) D base cost, C base cost; (6) D base cost, C high cost; (7) D high cost, C low cost; (8) D high cost, C base cost; (9) D high cost, C high cost. Incentive payment cash flow assumes incentives entirely spread out over time, in equal annual payments

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Appendix C: Supporting Information for Chapter 5

ECO-TOILETS QUESTIONNAIRE: CAPE COD, MASSACHUSETTS

Thank you very much for helping us with this important study!

This study is part of my ongoing research into some of the solutions that have been proposed to mitigate possible water pollution problems on Cape Cod. For my Ph.D. dissertation, I'm trying to understand how Cape Cod residents feel about water quality, as well as where householders and engineers might agree, and where they might disagree, about which sanitation technologies might be good, sustainable choices for households.

Your participation is entirely voluntary. You can participate no matter how much or how little you know about eco-toilets. **We want to hear from everyone.** We'll also tell you a little bit more about eco-toilets as we go, so if you're not very familiar with them you can learn a bit more about what they are and how they work – just look for "**Note**" following a question to get more information.

None of the questions in this survey are required and you can stop participating at any time, but the more questions you answer, the better we can understand what people think about eco-toilets. Even if you're not familiar with eco-toilets, your insights are very important to us. We're not looking for "correct" answers, we want to know what your thoughts and perceptions are, so please answer as honestly as you can.

The survey has a total of 45 questions; the entire survey should take approximately 15-20 minutes to complete. There are no known risks from participating. There will be no costs for participating other than the time it takes to complete the questionnaire and the envelope and stamp to mail it to us. To protect your privacy, your name, email address, home address, and other personally identifiable information **will not be asked** in the questionnaire and **will not be associated** with your answers to the questionnaire. We will destroy mailing envelopes, so your return address will not be kept.

We will make the results of the study publicly available on completion of the study, so you will have access to the information gained from the study. We'll post these results at http://sites.utexas.edu/eco-toilets/ as soon as they're available.

If you have any questions about the study, you can contact me, Alison Wood, at alisonwood@utexas.edu. This study has been reviewed by The University of Texas at Austin Institutional Review Board and the study number is 2014-09-0013. If you have questions about your rights or are dissatisfied at any time with any part of this study, you can contact, anonymously if you wish, the Institutional Review Board by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

Please return your finished questionnaire to: Alison Wood, Dept. of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Mail Stop C1786, 301 E. Dean Keeton St., Austin, TX 78712.

Q1 What town do you live in, or own or rent a home in?

- ❍ Bourne, MA
- ❍ Brewster, MA
- ❍ Dennis, MA
- ❍ Falmouth, MA
- ❍ Harwich, MA
- ❍ Hyannis, MA
- ❍ Mashpee, MA
- ❍ Sandwich, MA
- ❍ Yarmouth, MA
- ❍ Elsewhere on Cape Cod
- ❍ Somewhere other than Cape Cod

[If you live somewhere other than Cape Cod, you can return to http://sites.utexas.edu/eco-toilets to download a slightly shortened version of the survey that's more appropriate for you. If you'd rather complete this version, please SKIP questions 14, 18, 39, and 40, and answer the other questions to the best of your ability, substituting your own location for Cape Cod as appropriate.]

Q2 Are you a primary decision maker with respect to maintaining a home in Cape Cod?

- ❍ Yes, because I am an owner of the home
- ❍ Yes, because of my relationship to the owner of the home or my role as home caretaker
- ❍ Yes, because I rent or lease the home on a long-term basis (more than 3 months)
- ❍ Only minor decisions, not major renovations
- ❍ I have no influence over home maintenance

Q3 Have you ever used an eco-toilet?

Note: Eco-toilets in this survey means composting toilets and urine diversion toilets. Composting toilets collect both urine and feces in a container below the toilet, often in the basement or cellar. The waste is composted to make it safer to handle; the waste contains nutrients such as nitrogen, as well as organic material that can enrich soil. Urine diversion toilets collect urine in a tank either in the basement or buried outdoors; feces can be collected separately in a composting container or can be flushed to a septic tank or sewer system just as with a normal toilet. Urine contains most of the nutrients found in human waste, and typically has less bacteria than feces. Urine can be stored or heated to make it safer to handle.

- ❍ Yes, composting toilet
- ❍ Yes, urine diversion toilet
- ❍ Yes, both composting and urine diversion toilets
- ❍ No, neither
- ❍ Not sure

[If you answered "No" to question 3, please skip questions 4 and 5.]

Q4 Do you currently have one or more eco-toilets installed in your home? **Please check all that apply**.

- ❑ Composting toilet(s)
- ❑ Urine diversion toilet(s)
- ❑ No, neither

Q5 Please rate your overall experience using eco-toilets.

- ❍ It's just as good as using regular toilets
- ❍ It's better than using regular toilets/I prefer eco-toilets
- ❍ It's worse than using regular toilets/I prefer regular toilets
- ❍ I've never used an eco-toilet or I don't remember what it was like
- ❍ Other (please specify) ____________________

Q6 Would you be willing to use an eco-toilet in a friend's home?

- ❍ 1 - Absolutely not
- ❍ 2
- ❍ 3
- ❍ 4 - Neutral
- ❍ 5
- ❍ 6
- ❍ 7 - Completely willing

Q7 If your place of work, or a similar place you visit frequently, had both eco-toilets and regular toilets installed, which would you choose to use?

- ❍ Regular toilets, always (if available)
- ❍ Eco-toilets, always (if available)
- ❍ Eco-toilets, only if urinating (and if available)
- ❍ Willing to try eco-toilets at least once
- ❍ No preference/either one

Q8 All else equal, would you be willing to stay at a hotel or rent temporary lodgings for a short time if the lodgings had eco-toilets installed instead of regular toilets?

- ❍ 1 - Absolutely not
- ❍ 2
- ❍ 3
- ❍ 4 - Neutral
- ❍ 5
- ❍ 6
- ❍ 7 - Completely willing

Q9 Based on whatever knowledge and experience you currently have (or don't have) of eco-toilets, would you be willing to install them in your home?

- ❍ 1 - Absolutely not
- ❍ 2
- ❍ 3
- ❍ 4 - Neutral
- ❍ 5
- ❍ 6
- ❍ 7 - Completely willing

Q10 Did any of the following influence your response to the previous question (question 9)? **Please check all that apply**.

- ❑ Environmental benefits
- ❑ Environmental risks
- ❑ Cost benefits/lower costs
- ❑ Cost risks/higher costs
- ❑ Health risks
- ❑ Other practical reasons
- ❑ None of the above

Q11 Some people have logistical questions they would like answered before choosing whether or not to install eco-toilets in their homes. Please rate how important it is to you to have each of the following questions answered before choosing to install eco-toilets in your home. Please rank the items in order from 1=most important to have answered to 10=least important to have answered.

______ Something not listed here (please specify) ____________________________________

______ How much does it cost?

______ How does it work?

______ Are there limitations on the number or location of toilets?

______ Can my existing plumbing be used?

______ What do I do with toilet paper?

______ What do I do with the collected waste?

______ Is it easy enough that a child can use it properly, or a guest can use it without training?

______ Is it comfortable to use?

______ Can I contract out the maintenance and how much would that cost?

Q12 Some people have other questions they would like answered before choosing whether or not to install eco-toilets in their homes. Please rate how important it is to you to have each of the following questions answered before choosing to install eco-toilets in your home. Please rank the items in order from 1=most important to have answered to 9=least important to have answered.

______ Something not listed here (please specify) ____________________________________

______ Will it smell?

______ Will it attract insects or rodents?

______ Will I ever need to see or touch the collected waste?

______ Can I use the collected waste as fertilizer?

______ Can my children or my pets access the waste inside the container?

______ How likely it is that the waste container will leak?

______ What measures are in place to protect my and my family's health?

______ How will this affect my home's property value?

Q13 Do you have any other thoughts or comments you would like to share with us about eco-toilets?

Your answers to the following questions will help us better understand whether or not there is a connection between interest in eco-toilets and concerns about water quality. Remember, we're not looking for "correct" answers or what experts in this would say; we want to know what **your** thoughts and feelings are.

Q14 How do you feel the water quality of coastal waters and bays on Cape Cod has changed over the past 10 years?

- ❍ 1 - Gotten better
- ❍ 2
- ❍ 3 - No change
- ❍ 4
- ❍ 5 - Gotten much worse
- ❍ Not sure

Q15 How much of a problem do you think water pollution is in your geographic region?

- 1 - Not a problem at all
- 2
- 3
- 4
- 5
- 6
- 7 – A very significant problem

Q16 How much are you **directly** affected by water pollution (for example, property value, ability to swim or fish, tourism income, general enjoyment of the local environment, etc.)?

- 1 - Not affected at all
- 2
- 3
- 4
- 5
- 6
- 7 - Very much affected

Q17 Please indicate how much you agree or disagree with this statement: “Ordinary or conventional septic systems (*i.e.*, not “innovative” or “advanced”) do not contribute to local water pollution if they are functioning properly.”

Note: “Ordinary” or “conventional” septic systems (*i.e.*, Title V systems) are the most common kind, with a septic tank and some sort of drainage or leaching field or pits.

- 1 - Strongly disagree
- 2
- 3
- 4 - Neutral
- 5
- 6
- 7 - Strongly agree

Q18 Which of the following wastewater systems do you think would be the most effective in improving water quality in Cape Cod's coastal waters and bays? Please rank the items in order from 1=most effective to 5=least effective.

Note: "Ordinary" or "conventional" septic systems (*i.e.*, Title V systems) are the most common kind, with a septic tank and some sort of drainage or leaching field or pits. "Innovative" or "advanced" septic systems typically have additional underground units to provide additional treatment, control panels, and frequent (a few times per year) checkups by maintenance providers.

______ Something not listed here (please specify) ________________________________

______ Centralized wastewater treatment plant with sewer network

______ Eco-toilets

______ Innovative or advanced septic system

______ Ordinary or conventional septic systems (*i.e.*, not "innovative" or "advanced"), if all are working properly and regularly inspected

Q19 Who do you think is the most responsible for improving water quality in Cape Cod's coastal waters and bays? Please rank the items in order from 1=most responsible to 5=least responsible.

______ Something not listed here (please specify) ________________________________

______ Municipal government

______ State or federal government

______ The Cape Cod Commission (the land use planning, economic development, and regulatory agency for Cape Cod)

______ Local engineers and scientists

______ Homeowners/citizens

Q20 Is there anything else you'd like to say about wastewater on Cape Cod or any sanitation technologies or other solutions that have been proposed to solve the (supposed) problem of water pollution?

The following questions ask about some more general perceptions and attitudes.

Q21 Please indicate how much you agree or disagree with the following statements.

	1 - Strongly disagree	2	3	4	5 - Strongly agree
"Humans have the right to modify the natural environment to suit their needs."	❍	❍	❍	❍	❍
"When humans interfere with nature it often produces disastrous consequences."	❍	❍	❍	❍	❍
"Human ingenuity will ensure that we do NOT make the earth unlivable."	❍	❍	❍	❍	❍
"Humans are severely abusing the environment."	❍	❍	❍	❍	❍
"The Earth has plenty of natural resources if we just learn how to develop them."	❍	❍	❍	❍	❍

Q22 Please rate how disgusting you would find each of the following experiences:

	1 - Not disgusting at all	2	3 - Moderately disgusting	4	5 - Extremely disgusting
You are about to drink a glass of milk when you smell that it is spoiled.	❍	❍	❍	❍	❍
You are walking barefoot on concrete and step on an earthworm.	❍	❍	❍	❍	❍
A friend offers you a piece of chocolate shaped like dog-doo.	❍	❍	❍	❍	❍
You take a sip of soda and realize that you drank from the glass that an acquaintance of yours had been drinking from.	❍	❍	❍	❍	❍

Q23 How severe are the potential negative consequences of using eco-toilets in your home?

❍ 1 - Not severe at all
❍ 2
❍ 3
❍ 4
❍ 5
❍ 6
❍ 7 - Very severe

Q24 How valuable are the potential positive consequences of using eco-toilets in your home?

- ❍ 1 - Not valuable at all
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5
- ❍ 6
- ❍ 7 - Very valuable

Q25 To what extent do you think the risks associated with eco-toilets are acceptable to obtain the benefits?

- ❍ 1 - Not acceptable at all
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5
- ❍ 6
- ❍ 7 - Completely acceptable

Q26 To what extent do you think that any potential risks associated with eco-toilets are new risks or old and familiar risks?

- ❍ 1 - Completely old and familiar
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5
- ❍ 6
- ❍ 7 – Completely new

Q27 Please read the following list of choices. In each case, please indicate which is the better choice or if both choices are equally good.

Which is the better choice:	❍ Making a cash payment of $100 today	❍ Making a cash payment of $120 a year from now	❍ Both equally good
Which is the better choice:	❍ A $100 gift today	❍ A $110 gift a year from now	❍ Both equally good
Which is the better choice:	❍ Making a cash payment of $100 today	❍ Making a cash payment of $135 a year from now	❍ Both equally good
Which is the better choice:	❍ A $100 gift today	❍ A $150 gift a year from now	❍ Both equally good

Q28 If your town offered you a one-time cash incentive to install eco-toilets in your home, how much money would they have to offer you to convince you to install eco-toilets?

Q29 If your town reduced your water bill every year for the next ten years as an incentive to install eco-toilets in your home, how much would they have to reduce your bill by (each year) to convince you to install eco-toilets?

Please answer all of these questions about yourself, regardless of whether or not you're an owner of a home. If you own more than one property on Cape Cod, please choose one and answer all questions about that one property. You can clarify this in the final open-ended question as needed.

None of the questions in this survey are required, but the more questions you answer, the better we can understand what people think about eco-toilets.

Q30 What year were you born?

Q31 What is your gender?

Q32 What is your annual 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

Q33 What is the highest degree or level of school you have completed?

- No schooling completed
- Kindergarten to grade 12 (no diploma)
- High school diploma or GED
- Some college, no degree
- Associate's degree (for example, AA, AS)
- Bachelor's degree (for example, BA, BS)
- Graduate or professional degree (for example, MA, MBA, MD, JD, PhD)
- Technical training leading to a certificate

Q34 What is your race?

- White
- Black or African American
- American Indian or Alaska Native
- Asian
- Native Hawaiian or other Pacific Islander
- Some other race

Q35 Are you of Hispanic, Latino, or Spanish origin?

- Yes
- No

Q36 Including you, how many people were residing in your home on Cape Cod on Monday, September 14, 2015?

Q37 Were any children under the age of 18 residing in your home on Cape Cod on Monday, September 14, 2015?

- ❍ Yes
- ❍ No

Q38 Please indicate which of the following you have **chosen to install** in your home. Please indicate separately anything that was **already installed** in the home when you bought or leased it. **Please check all that apply.**

- ❑ Energy Star appliances
- ❑ Low flow or Water Sense fixtures (faucets, showerheads)
- ❑ Solar panels
- ❑ Some of these were already installed by a previous owner (please specify) ____________________

Q39 Have you participated in any workshops or meetings on the Cape related to wastewater? Please feel free to add details in the space provided below.

- ❍ Yes
- ❍ No

Q40 Please feel free to add details:

Q41 How long have you owned your home on Cape Cod?

Q42 Is your home on Cape Cod your...

- ❍ Primary home
- ❍ Secondary or vacation home
- ❍ Property exclusively for rental
- ❍ Property that you use sometimes and rent out sometimes

Q43 Is your home on Cape Cod primarily occupied or rented/leased...

- ❍ Year-round, by you or your family
- ❍ Year-round, by someone else
- ❍ Seasonally, by you or your family
- ❍ Seasonally, by someone else
- ❍ On a monthly or other short term basis (please explain as needed) ____________________

Q44 Is your current wastewater system a...

Note: "Ordinary" or "conventional" septic systems (*i.e.*, Title V systems) are the most common kind, with a septic tank and some sort of drainage or leaching field or pits. "Innovative" or "advanced" septic systems typically have additional underground units to provide additional treatment, control panels, and frequent (a few times per year) checkups by maintenance providers.

- ❍ Ordinary or conventional septic system (*i.e.*, not "innovative" or "advanced")
- ❍ Innovative or advanced septic system
- ❍ Sewer connection to a central treatment plant
- ❍ Other (please specify) ____________________

Q45 Is there anything else you'd like to share with us about any of the subjects covered in this survey, or about the survey itself?

ADDITIONAL RESULTS

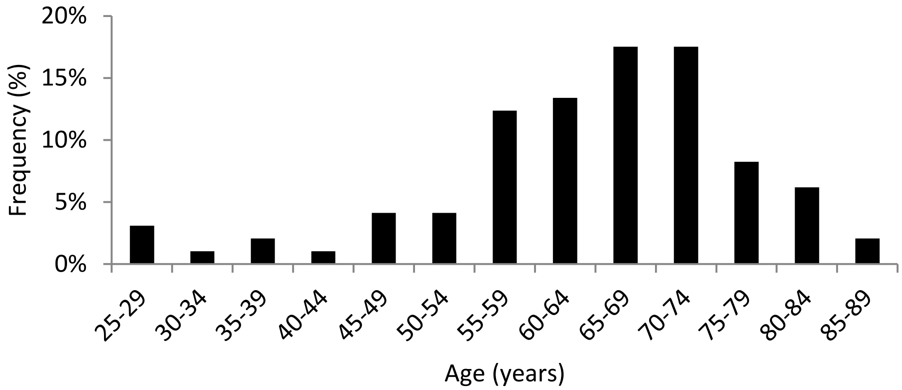

Figure C1. Respondent age.

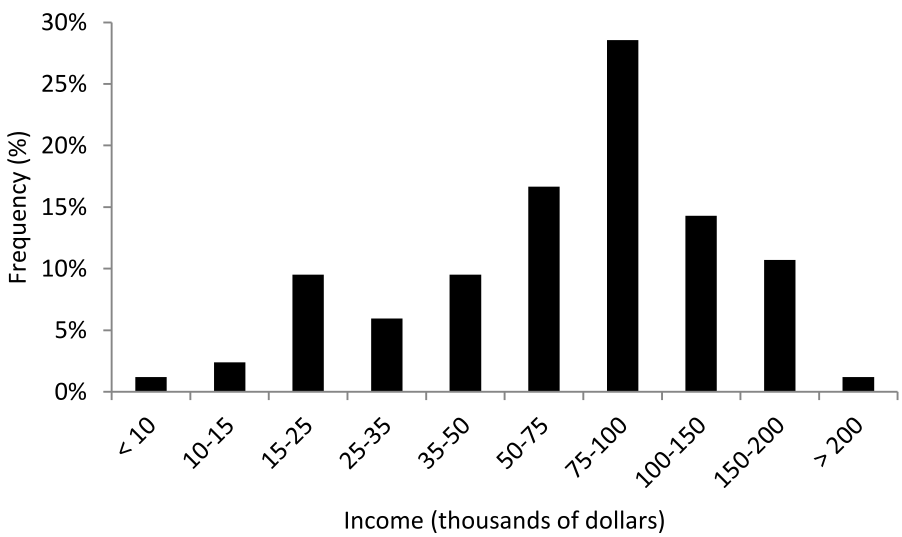

Figure C2. Respondent household income in the thousands of dollars.

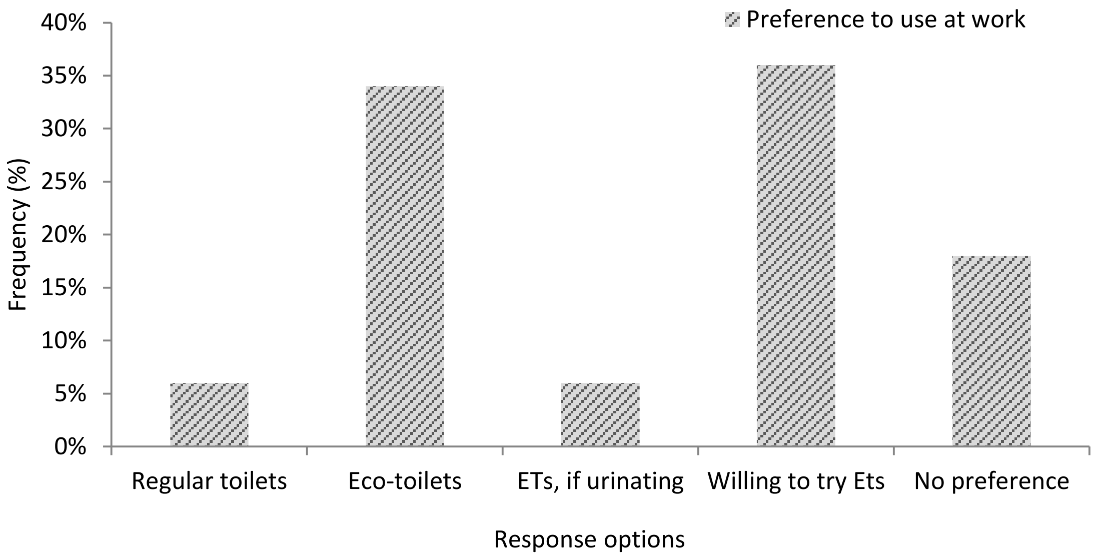

Figure C3. Responses to item on willingness to use eco-toilets at work.
Notes: If your place of work, or a similar place you visit frequently, had both eco-toilets and regular toilets installed, which would you choose to use?

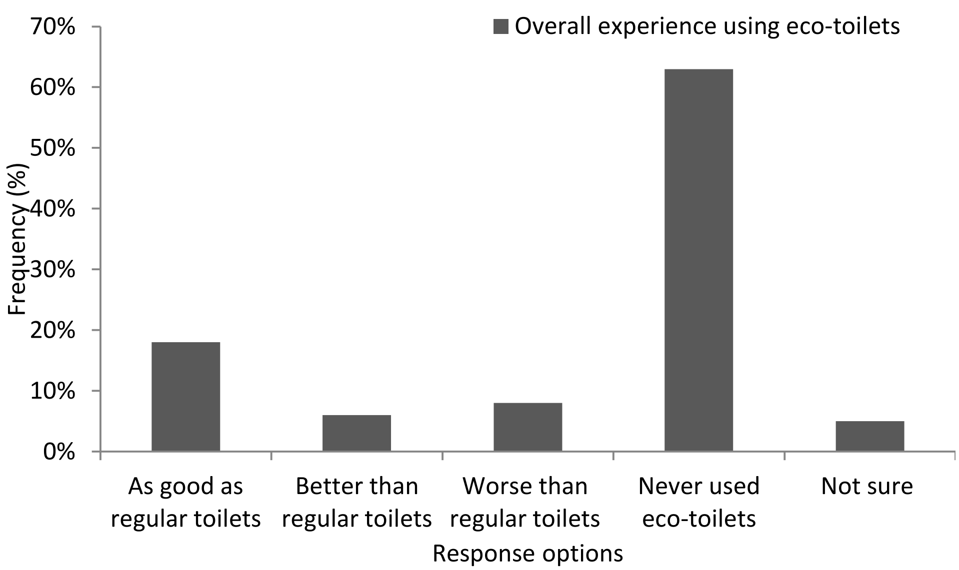

Figure C4. Responses to item on perceptions of eco-toilets.
Notes: Please rate your overall experience using eco-toilets.

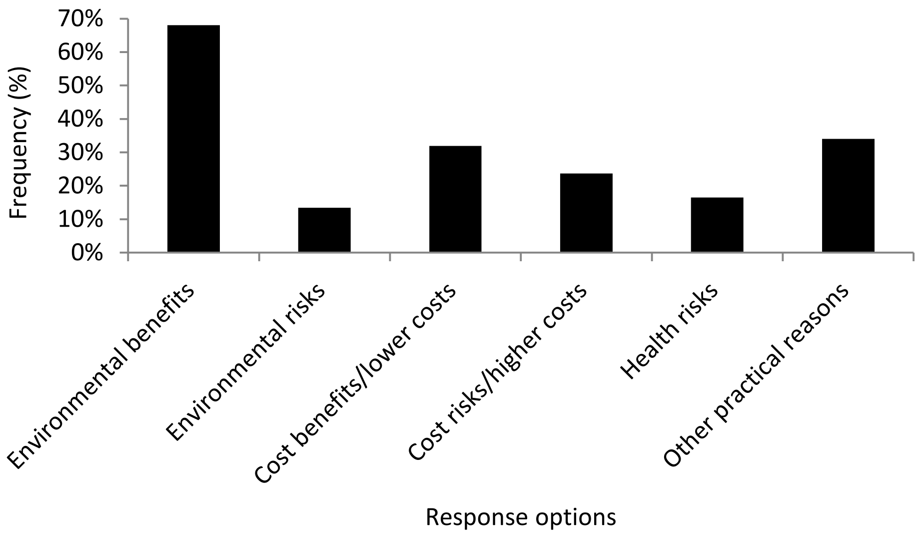

Figure C5. Responses to item on factors influencing willingness to install eco-toilets.
Notes: Did any of the following influence your response to the previous question (question 9)? Please check all that apply. (Q9 Based on whatever knowledge and experience you currently have (or don't have) of eco-toilets, would you be willing to install them in your home?)

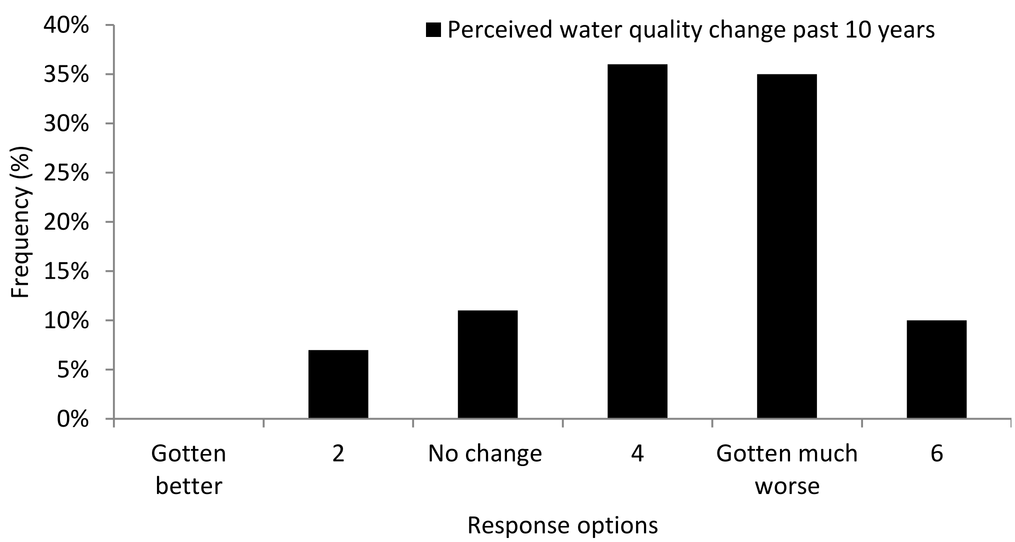

Figure C6. Responses to item on perceptions of local water quality.
Notes: How do you feel the water quality of coastal waters and bays on Cape Cod has changed over the past 10 years?

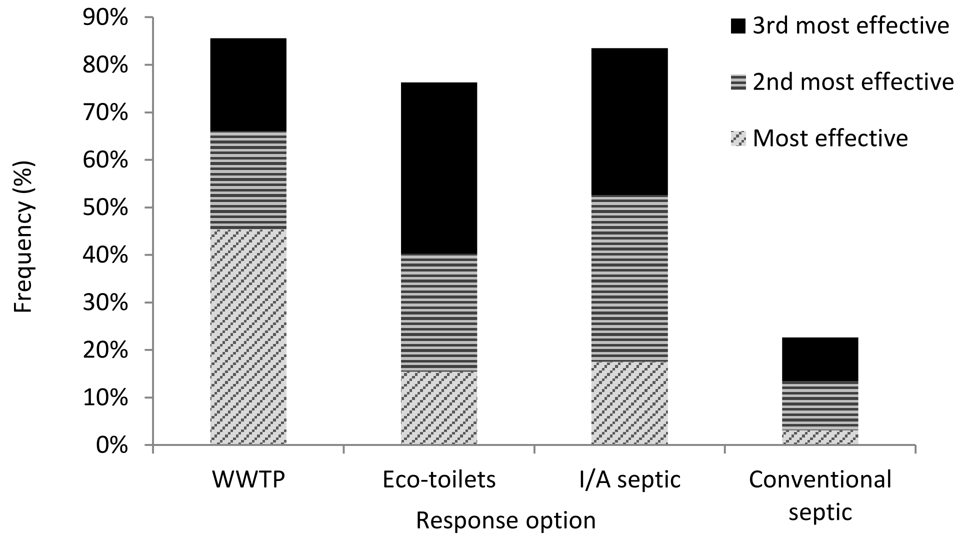

Figure C7. Responses to item on effectiveness of solutions to water pollution.
Notes: Which of the following wastewater systems do you think would be the most effective in improving water quality in Cape Cod's coastal waters and bays? Please rank the items in order from 1=most effective to 5=least effective.

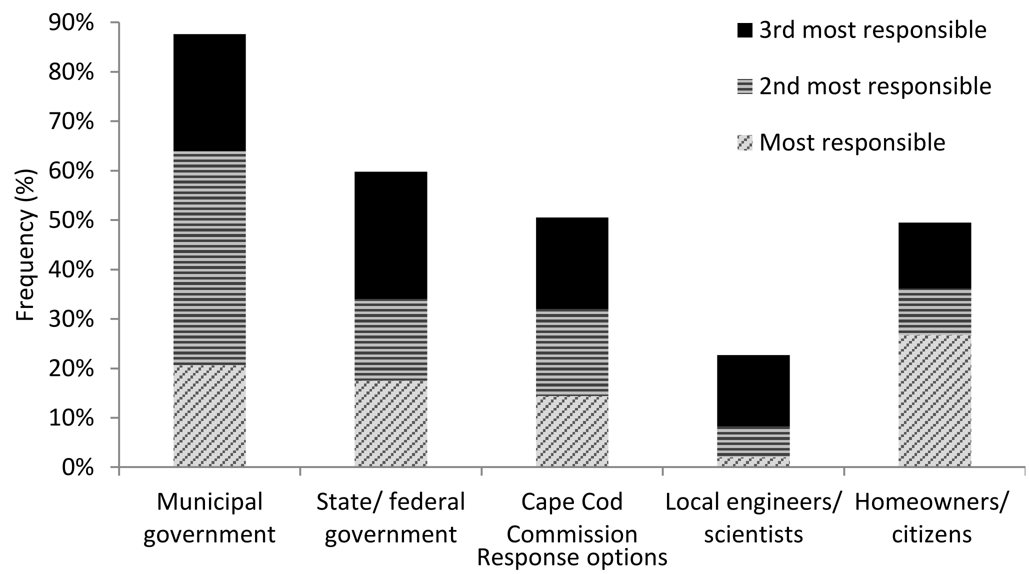

Figure C8. Responses to item on parties responsible for improving water quality.
Notes: Who do you think is the most responsible for improving water quality in Cape Cod's coastal waters and bays? Please rank the items in order from 1=most responsible to 5=least responsible.

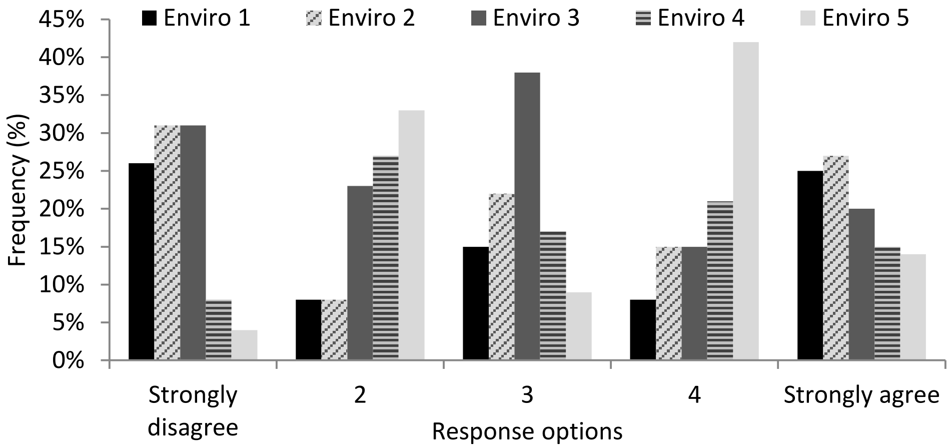

Figure C9. Responses to item on environmental attitudes.
Notes: Please indicate how much you agree or disagree with the following statements. 1) Humans have the right to modify the natural environment to suit their needs. 2) When humans interfere with nature it often produces disastrous consequences. 3) Human ingenuity will ensure that we do NOT make the earth unlivable. 4) Humans are severely abusing the environment. 5) The Earth has plenty of natural resources if we just learn how to develop them.

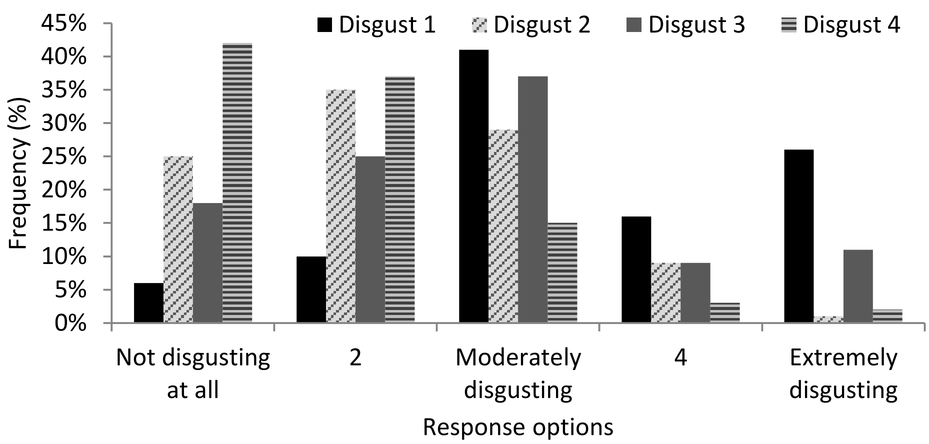

Figure C10. Responses to item on personal norms (sensitivity to disgust).
Notes: Please rate how disgusting you would find each of the following experiences: 1) You are about to drink a glass of milk when you smell that it is spoiled. 2) You are walking barefoot on concrete and step on an earthworm. 3) A friend offers you a piece of chocolate shaped like dog-doo. 4) You take a sip of soda and realize that you drank from the glass that an acquaintance of yours had been drinking from.

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