Published January, 2012

Development of Environmental Thresholds for Streams in Agricultural Watersheds

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Global increases in consumption of chemical nutrients, application of pesticides, and water withdrawal to enhance agricultural yield have resulted in degraded water quality and reduced water availability. Efforts to safeguard or improve environmental conditions of agroecosystems have usually focused on managing on-farm activities to reduce materials loss and conserve habitat. Another management measure for improving environmental quality is adoption of environmental performance standards (also called *outcome-based standards*). This special collection of six papers presents the results of four years of research to devise scientifically credible approaches for setting environmental performance standards to protect water quantity and quality in Canadian agriculturally dominated watersheds. The research, conducted as part of Canada's National Agri-Environmental Standards Initiative, aimed to identify Ideal Performance Standards (the desired environmental state needed to maintain ecosystem health) and Achievable Performance Standards (the environmental conditions achievable using currently available and recommended best available processes and technologies). Overviews of the papers, gaps in knowledge, and future research directions are presented. As humans, livestock, and wildlife (both terrestrial and aquatic) experience greater pressures to share the same limited water resources, innovative research is needed that incorporates a landscape perspective, economics, farm practices, and ecology to advance the development and application of tools for protecting water resources in agricultural watersheds.

J. Environ. Qual. 41:1–6 (2012)
doi:10.2134/jeq2011.0338
Posted online 8 Dec. 2011.
Received 16 Sept. 2011.
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The 20th century saw great development in agricultural technologies and production systems. Between 1950 and 1985, the success of the Green Revolution in reducing food shortages in several parts of the world was linked primarily to new crop varieties designed to maximize yields, facilitate multiple cropping, and resist diseases. To achieve the full potential yield of these improved varieties and to protect them against diseases and pest infestation, it was essential to provide crops with chemical nutrients, use pesticides, and ensure appropriate water conditions (through either irrigation or drainage). The result was a global increase in consumption of chemical nutrients, application of pesticides, and water withdrawal (Mosier, 2002; Schröder et al., 2011; Wada et al., 2011). Over time, some of these advances have clearly impaired environmental health, resulting in degraded water quality and reduced water availability. For example, the need for additional water (semiarid landscapes) or to route excess water off fields (humid landscapes) can have positive effects on water quality (e.g., proper drainage reduces surface runoff and erosion, and loss of nitrogen by denitrification); yet such actions can also have negative effects through increased leaching or runoff of agrochemicals and pathogens to surface and groundwaters. Similarly, while application of pesticides has increased the efficiency of fertilizer use, this practice has resulted in pesticide losses to the atmosphere and subsequent deposition from the atmosphere to surface water and nonagricultural lands, as well as runoff and leaching to surface and groundwaters. Alterations to soil conditions caused by tillage and cropping patterns may cause soil degradation, which can lead to less infiltration of water into soil and, thus, increased runoff and movement of nutrients and pesticides to surface waters. Finally, drainage of wetlands and channelization of streams have increased the area of agriculturally productive soils but have also modified local ecosystems and changed the pattern of water partitioning between evapotranspiration, streamflow, and infiltration. Costs associated with agricultural impairments to surface waters are

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Abbreviations: APS, Achievable Performance Standards; BMP, beneficial management practice; EC, Environment Canada; IPS, Ideal Performance Standards; NAESI, National Agri-Environmental Standards Initiative; TN, total nitrogen; TP, total phosphorus.

not inconsequential: the cost of water pollution from agriculture in the United Kingdom, for example, was estimated in 2003–2004 at approximately £500 million (~US$850 million) annually (Parris, 2011), while the cost of reducing annual nitrate N loadings to the Gulf of Mexico by 30% (with a concomitant reduction in P of 36%) is estimated to be US$1.4 billion yr^{-1} (Rabotyagov et al., 2010).

Efforts to safeguard or improve environmental conditions of agroecosystems while maintaining agricultural and human food supply have traditionally focused on managing on-farm activities to reduce materials loss and conserve habitat (e.g., correct management of chemicals and manure, improved animal husbandry and crop production systems, and interception of materials leaving the agricultural setting). These on-farm activities, often known as *beneficial management practices* (BMPs), have had varied success. Many field and modeling studies indicate that implementation of various BMPs can have positive effects on surface and groundwater quality (Cook et al., 1996; Edwards et al., 1997; Chaplot et al., 2004; Thomas et al., 2007). However, ineffectual placement or timing of BMPs in watersheds, lag effects arising from legacy conditions (e.g., historic land management), and vagaries in weather can sometimes offset anticipated improvements (e.g., Tomer and Locke, 2011).

Another management measure for improving environmental quality is adoption of environmental performance standards (also called *outcome-based standards*). Such standards specify the desired condition for an ecosystem or its elements. Although the desired ecological condition for a particular ecosystem may be debatable, the standards are usually established so as to result in negligible risk to biota (including humans), their functions, or any interactions integral to sustaining the health of ecosystems and designated resource uses. Many countries have had some form of environmental performance standards since the 1960s or 1970s, the most common being maximum allowable concentrations of substances in water. The standards, whether voluntary (e.g., criteria, guidelines, objectives, targets) or regulatory, have served as benchmarks for assessing potential or actual impairment of an ecosystem, evaluating efficacy of pollution control measures, and tracking progress in remediation of impaired ecosystems. Such standards also support programs with the theme of sustainable agriculture (i.e., the integration of environmental health, farm profitability, and viable rural communities) by contributing to the protection of natural capital and the benefits and services it provides to present and future generations.

Yet several challenges exist in defining environmental performance standards for agroecosystems:

1. Few if any portions of agricultural landscapes are undisturbed, or even minimally disturbed. Thus, it is difficult to identify reference conditions, i.e., the ecological conditions that existed before intensive agriculture.
2. Even if reference conditions could be defined, the goals of sustainable agriculture are to maintain, or restore, good ecological condition, not necessarily the natural or unmodified condition.
3. Impacts caused by the two stressors of greatest concern to fresh waters, namely nutrients and fine sediments, are largely due to changes to ecosystem structure and function (e.g., eutrophication or reduced habitat quality) and rarely to direct toxicity. This negates the use of standard toxicological tests for setting environmental performance standards for these stressors.

Development of environmental performance standards for water quality and quantity in agriculturally dominated watersheds therefore requires consideration of stressors that affect ecosystem condition (structure and function), the fact that these watersheds will (or can) not return to the unmodified condition, and that improvements will likely require staged interventions over a number of years.

Objective of This Special Collection

This special collection presents the results of four years of research to devise scientifically credible approaches for setting environmental performance standards for Canadian agricultural watersheds. The intent of these standards is to protect water resources in agricultural landscapes from deleterious change caused by excess nitrogen (N), phosphorus (P), sediments, pesticides, waterborne pathogens, and water withdrawal. The research was conducted as part of a special 4-yr (2004–2008) program, known as the National Agri-Environmental Standards Initiative (NAESI), which was undertaken collaboratively between Canada's federal departments of environment (Environment Canada, EC) and agriculture (Agriculture and Agri-Food Canada, AAFC). The standards were to be nonregulatory, nationally consistent (with regional application), and scientifically defensible. The research and resulting environmental standards developed under NAESI were aligned along four themes: water (quality—nutrients, sediments, pathogens; quantity), pesticides (air and water), air quality, and terrestrial biodiversity. Here we present approaches developed for setting standards for water quality and quantity.

Two types of standards were recognized under NAESI:

1. Ideal Performance Standards (IPS), specifying the desired environmental state needed to maintain ecosystem health.
2. Achievable Performance Standards (APS), specifying environmental conditions that could realistically be achieved using currently available and recommended best available processes and technologies (i.e., BMPs).

Hence, IPS define the maximum level of a chemical or physical condition at which no known or anticipated adverse effects on ecological condition would occur, whereas APS define the level of a chemical or physical condition that is technically feasible to achieve. The theoretical relationship between environmental performance standards and the current situation commonly found in agriculture-dominated landscapes in Canada indicates that as an agricultural physicochemical stressor (e.g., P, pesticides, or suspended sediments) increases, the biological impact (i.e., proliferation of cyanobacteria, loss of critical species) on the environment is also amplified (Chambers et al., 2011). In many situations, the environmental state that would ensure sustainable ecosystem health (IPS) would be different than either the present situation or that which could be achieved with the implementation of currently available and economically feasible BMPs (APS). Over time, however, development and implementation of new BMPs could move the current situation toward the ideal situation (IPS), thereby minimizing the rate of degradation or loss of ecosystem goods and services.

Environmental Thresholds for Agricultural Watersheds: Paper Summaries

Historically, development of standards to reduce water pollution focused on setting limits for fecal indicator bacteria to protect human health and for toxic chemicals to protect health of humans and other animals. Such standards are based on endpoints determined from epidemiological studies (for human health effects) and controlled laboratory experiments. Under NAESI, new or revised IPS were proposed for several toxic chemicals including nitrate and certain pesticides (Demers and Jiapizian, 2009; Guy, 2009). These results were not included in this special collection, which, instead, focuses on devising approaches for setting (i) IPS for stressors that are not directly toxic but rather change the structure or function of ecosystems and (ii) APS for a variety of stressors (some of which are toxic). The papers forming this special collection present new frameworks for devising IPS and APS and, depending on data availability and the maturity of the scientific discipline, numerical standards for either a few watersheds or networks of watersheds spanning the agricultural regions of Canada.

Setting Ideal Performance Standards

Farmers around the world rely at least in part on inorganic fertilizers to sustain and improve crop yields. But overuse of P and N can lead to eutrophication, often manifested as cyanobacterial blooms in lakes and "dead zones" in coastal waters (Smith et al., 2006). A further issue is that P comes from phosphate rock, a nonrenewable resource for which there is a limited supply, leading to potential shortages (Vaccari and Strigul, 2011). Chambers et al. (2012) present a framework for devising IPS for N and P and then apply it to develop standards for seven agricultural regions in Canada. The standards, expressed as mean streamwater total P (TP) and total N (TN) concentrations, were calculated using the following steps: Step 1—compute chemically based thresholds for TP and TN as the mean of four approaches (three percentile approaches applied in the United States, Australia and New Zealand, and Canada, and a regression tree approach relating TP or TN to percent agricultural land cover); Step 2—determine change-points in relationships between algal and benthic invert indices and nutrient concentrations; Step 3—apply a decision tree to determine whether the chemically based thresholds (Step 1) or the biologically based thresholds (Step 2) are the numerical IPS. Although a number of agencies and researchers are investigating approaches for setting scientifically credible standards for N and P to protect aquatic ecosystems from the deleterious effects of eutrophication (e.g., USEPA 2000), the framework proposed by Chambers et al. (2012) presents a novel approach for integrating the often long record of water chemistry data with usually less frequently sampled biotic data to devise credible standards for N and P to protect biotic integrity of agricultural streams.

Watersheds in livestock-dominated regions are vulnerable to waterborne pathogen contamination from livestock fecal wastes entering water courses either directly (through instream watering) or indirectly (runoff of manure from fields, storage facilities, and barns, yards, and fields). Although many countries have drinking water and recreational water quality standards for protecting human health from waterborne pathogens (usually based on *Escherichia coli*), Edge et al. (2012) show that a variety of waterborne pathogens were detected in more than 80% of water samples that met the Canadian recreational water quality guideline for *E. coli*. Hence, simple use of an *E. coli* guideline for recreational waters as an environmental benchmark for nonrecreational agricultural streams may not be appropriate for protecting ecosystem health. Rather, Edge et al. (2012) propose an innovative approach for setting IPS based on using natural background occurrences of waterborne pathogens (e.g., from wildlife) at reference sites in agricultural watersheds. Their proposed environmental IPS for *E. coli* corresponds to the upper 95% confidence interval for the annual mean number of waterborne pathogen species in water samples from reference sites. The approach developed by Edge et al. (2012) represents the first published attempt to derive an ecologically based standard for waterborne pathogens.

Agriculture can cause soil exposure and compaction, thereby contributing to increased sediment inputs to streams and, as a result, threatening their ecological integrity (Waters, 1995). Monitoring efforts have largely focused on measuring suspended sediment and associated measures (e.g., turbidity), but the effects of increased deposited (or bedded) sediment are also problematic: smothering and scouring of benthic biota, increased drift of benthic macroinvertebrates, and impairment of critical habitat used by fish and invertebrates (Wood and Armitage, 1997; Henley et al., 2000). Despite widespread acknowledgment that streams are increasingly degraded because of excessive sedimentation, few well-developed and validated approaches exist for assessing the extent of deposited sediments in stream ecosystems. Sutherland et al. (2010) assessed a suite of geomorphic metrics for their suitability as indicators of deposited sediment. For six of these geomorphic metrics (percentage of fines <2 mm measured using three techniques, percentage of fines <6.35 mm, median particle size, and relative bed stability), Benoy et al. (2012) developed provisional IPS for the "potato belt" of northwestern New Brunswick, Canada, with IPS calculated as both the 25th percentile of all data and the intercept of a plot of the geomorphic metric versus percentage agricultural land cover. These geomorphic standards were cross-calibrated by comparison with change-points in relationships between indices of benthic invertebrate composition and geomorphic metrics. Benoy et al. (2012) suggest that with sufficient data, it is possible to establish IPS for deposited sediments that signify a change from least-disturbed conditions and will reduce the risk of sedimentation degrading benthic ecosystems.

Agricultural activities can have a strong influence on availability of water to sustain natural ecosystems, either directly (through abstraction of water for irrigation, retention of water in ponds and reservoirs, and augmentation of flow through enhanced drainage) or indirectly (through conversion of native vegetation to crops, and management practices to enhance their yields). Answering the question "how much water does a river need to sustain the aquatic ecosystem?" has focused historically on maintaining minimum flows to sustain a fish species of interest, often a salmonid (Arthington et al., 2006). However, protecting a single species may fail to protect other components of an ecosystem, especially when those other components rely on temporal variation in flows not recognized in a single-species model. Peters et al. (2012) propose an alternative framework for setting ecological IPS for instream flows that links a hydrological assessment tool with an ecological assessment tool to quantify deviation between the current and the reference regime, first for a suite of hydrological indicators and second for ecological indicators sensitive to variation in the magnitude and timing of stream flow. Significant deviation between the observed and reference hydrological regime triggers the need for an ecological assessment, and detection of significant deviations in the ecological assessment results in a designation of impairment. Although others (e.g., Poff et al., 2010) recognize the need to link ecological and hydrological assessment in development of instream flow standards, Peters et al. (2012) have explicitly incorporated a purposeful ecological assessment tool developed for wadable agricultural streams.

Setting Achievable Performance Standards

Ideal Performance Standards aim to define environmental conditions that protect ecological condition. In practice, however, this state may not be achievable in the near future, and efforts to move the current situation toward the ideal situation will require implementation of recommended management actions, agricultural practices, and available technologies (i.e., BMPs). Achievable Performance Standards are intended to identify water chemistry improvements that could be realized through the implementation of various scenarios of alternative land management practices, including BMPs.

Rousseau et al. (2012) present a novel approach for defining APS for pesticides that could be attained following implementation of recommended BMPs. Pesticides, including herbicides, insecticides, and fungicides, are widely used in agriculture. Many of the chemicals used in pesticides pose threats to human health and the environment, and a number are persistent, highly mobile, and capable of bioaccumulating. Ideal Performance Standards have been derived for a number of pesticides based on toxicological endpoints determined from controlled laboratory experiments (e.g., USEPA, 1986; CCME, 1999; ANZECC and ARMCANZ, 2000). In many locales, however, current in-stream pesticide concentrations are greater than IPS. Rousseau et al. (2012) applied an integrated hydrological modeling system (Gestion Intégrée des Bassins versants à l'aide d'un Système Informatisé, GIBSI) to define pesticide concentrations for six Canadian watersheds modeled under different scenarios: the reference (or current) situation and at least one of three BMP scenarios (addition of riparian buffer strip; reduction in pesticide application; riparian buffer strip + reduced pesticide application). For each watershed and each scenario, a cumulative distribution function curve was developed for a given pesticide based on results from about 30 model simulations using different weather data and random dates of pesticide application. For each scenario, the APS was defined as the 90th percentile of the cumulative distribution function curve calculated for each scenario. As expected, the APS values for BMP scenarios were less than APS values for the current situation for all six watersheds; notable, however, was the prediction that adoption of the tested BMPs would result in pesticide concentrations at the outlet of watersheds that were usually less than IPS (when available), which was not always the case for some upstream river reaches.

Unlike many pesticides that have toxicological IPS, suspended sediments and P are not inherently toxic but cause ecosystem changes through indirect effects such as water opacity, smothering or scouring (sediments), or eutrophication (P). Yang et al. (2012) propose APS for suspended sediments and soluble P based on comparison of modeled loads before and after BMP implementation. Using the Soil and Water Assessment Tool (SWAT), sediment and soluble P loads were modeled for a New Brunswick (potato-dominated) watershed following implementation of four commonly used BMPs (flow diversion terraces, fertilizer reductions, tillage methods, and crop rotations), singly and in combination. Sizable loads reductions (89% for sediments and 62% for soluble P) were predicted with a combination of crop rotation, flow diversion terraces, and either no-till (sediments) or fertilizer reduction (soluble P).

The modeling approaches applied by both Rousseau et al. (2012) and Yang et al. (2012) lend themselves to use by farmers or decision makers to assist with BMP selection. In the case of the approach developed by Rousseau et al. (2012), watershed maps are generated that show APS values for a specific pesticide and the likelihood of exceeding its IPS for a given river segment and scenario (current or choice of BMPs). Yang et al. (2012) produced charts that show the mean, maximum, and minimum load reductions predicted to occur in response to BMP application. In both cases, however, it should be noted that final decisions about implementing BMPs will most likely be based on social and economic, as well as environmental, considerations; the former two conditions (farm and/or rural social and economic conditions) were not considered under NAESI.

Gaps in Our Knowledge and Future Research Direction

The intended outcome of the research conducted under NAESI was to provide consistent, science-based environmental standards that (i) establish benchmarks against which environmental performance of the agriculture sector can be assessed; (ii) inform agri-environmental programming such as environmental farm planning; and (iii) contribute to a better understanding of the interactions between agriculture and the environment. The efforts described in the six papers in this special collection represent a considerable advancement in our understanding and management of agricultural landscapes. Their most important contribution is, however, the development of approaches or frameworks for computing standards. In the case of IPS frameworks, conventional assessment metrics (nutrients, sediments, flow, *E. coli*) are explicitly tied to ecological significance to generate standards for conventional metrics that are protective of environmental condition. In the case of APS, modeling schemes are applied that allow exploration of BMP effectiveness for pollution control and, in turn, stakeholder education.

Adoption of these standards may ultimately lead in turn to benefits for the agriculture sector by improving the sustainability of the industry; to the economy by improving understanding of environmental costs and benefits for agriculture; and for the public by contributing to a healthier environment, better quality of life, and sustainable management of natural resources for future generations.

The two types of standards, IPS and APS, together with economic analysis of implementation costs and societal objectives regarding environmental quality, can be used to guide management decisions now and in the future: IPS defines the ecological condition that is the ultimate objective, whereas APS is the technologically achievable target. The latter will undoubtedly change over time, trending toward the IPS as new agricultural crops, practices, and BMPs are developed (Chambers et al., 2011). As new ecological data become available (e.g., new indicators of community structure or function, or improved understanding of effects of stressors on aquatic biota) or new approaches develop for synthesizing complex data (e.g., multi-indicator responses to one or multiple stressors, or temporal changes in indicator response), IPS may also change and thus require reassessment of management actions. Although APS and even IPS may change over time with new data and knowledge, the papers in this special collection describe scientifically defensible approaches that will accommodate such new data and knowledge. Moreover, they represent an advance over previous approaches for establishing environmental standards that involved best professional judgment or identification of ecological conditions that existed before intensive agriculture.

Application of the frameworks presented in this special collection is, however, constrained by limited data both temporal (data sets often span only a few years) and spatial (only a small number of watersheds). Hence, it is presently a major challenge to verify the standards (both IPS and APS) that have been proposed. Monitoring data for verification of the proposed standards is therefore urgently required. Future research on criteria development will also benefit from consideration of interactions among stressors (i.e., flow, nutrients, pathogens, pesticides) and the combined effect of these multiple stressors on aquatic food webs. The six papers in this special collection tend to focus on smaller rivers in agriculturally dominated watersheds; future research will also need to be conducted to ensure that standards established for streams and rivers are also protective of downstream waterbodies such as lakes and coastal waters, with their very different seasonal cycles and mixing patterns.

Emerging holistic perspectives on environmental health call for recognizing the interconnections among humans, domestic animals, and the natural environment. As human and domestic animal populations grow, wildlife populations compress into smaller areas, and aquatic organisms experience limited water availability and impaired water quality, there will be an increased need to share the same limited water resources. Innovative research is needed that incorporates a landscape perspective, economics, farm practices, and ecology to advance environmental performance standards that will serve as tools for protecting water resources in agricultural watersheds.

Acknowledgments

The research described in this paper and others in this special collection were part of the National Agri-Environmental Standards Initiative (NAESI) and funded by Agriculture and Agri-Food Canada (AAFC) and Environment Canada (EC). The authors thank the contributors to the special collection of papers for their hard work in preparing manuscripts for publication in the *Journal of Environmental Quality*.

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