PÔLE D’EXPERTISE MULTIDISCIPLINAIRE EN GESTION
DURABLE DU LITTORAL DU LAC SAINT-PIERRE

Revue de littérature, version anglaise abrégée

SUSTAINABLE AGROECOLOGICAL PRACTICES, PROVISION OF ECOSYSTEM SERVICES, AND PERSPECTIVES FOR THE RESTORATION OF CULTIVATED FLOODPLAINS

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Document submitted to the Steering Committee of the *Pôle d'expertise multidisciplinaire en gestion durable du littoral du lac Saint-Pierre*, on February 15, 2019.

Bourgeois, B., Vaillancourt, M., Vanasse, A. (2019). Sustainable agroecological practices, provision of ecosystem services, and perspectives for the restoration of cultivated floodplains (abridged version). Pôle d'expertise multidisciplinaire pour la gestion durable du littoral du lac Saint-Pierre, Université Laval, Québec.

Cover photo: Julie Ruiz, 2016.

Financial partner:

Québec

In 2018, the Government of Québec launched an important research initiative to promote the restoration of the Lake Saint-Pierre ecosystem and its littoral zone by forming the *Pôle d'expertise multidisciplinaire en gestion durable du littoral du lac Saint-Pierre*. The *Pôle* is responsible for coordinating and proposing an intervention strategy for the development of sustainable agriculture practices in the littoral zone and for the restoration of natural habitats that would support conservation of Lake Saint-Pierre's ecosystem. Multidisciplinary collaborations are established to:

- develop crops and agricultural practices adapted to the specific context of the cultivated littoral zone of Lake Saint-Pierre that would positively impact its ecological integrity,
- evaluate the performance and impacts of agricultural activities and restoration projects socially, economically, environmentally, and on wildlife,
- propose a management strategy to provincial ministers based on the research results obtained that promotes sustainable agriculture in the littoral zone of Lake Saint-Pierre.

This document highlights key information for each section of the associated literature review and provides a non-exhaustive list of key research questions for the restoration of Lake Saint-Pierre's littoral zone.

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The Lake St-Pierre ecosystem

- Lake St-Pierre can be viewed as a hotspot for both biodiversity (Ramsar site and UNESCO Biosphere Reserve) and agricultural activities.
- During five to nine weeks starting in April, the water level of Lake Saint-Pierre increases. When the water level reaches 6.8 m in Sorel, approximately 28,000 ha of riparian and terrestrial areas around the lake are submerged. This occurs every two years on average (referred to hereafter as the 0–2 y littoral zone).
- In Lake Saint-Pierre's 0–2 y littoral zone, 5,264 ha are cultivated by 151 agricultural enterprises. Of these, 102 have less than 5% of their total cultivated area in the littoral zone, 40 between 5% and 20%, and nine more than 20%.
- Perennial and annual crops covered approximately 3% and 20%, respectively, of the littoral zone in 2014, representing a four-fold increase in the annual crop cover over the 1964–2014 period and a concurrent 10-fold decrease in the perennial crop cover.
- The ecosystem of Lake Saint-Pierre has experienced major environmental degradations, particularly notable by the abrupt decline of yellow perch populations over the last few decades.
- Yellow perch reproduce in shallow swamps, shrublands, and wet grasslands of littoral zone that are submerged during the spring.
- Yellow perch select areas for spawning that are characterized by a vegetal substrate including submerged shrub branches, dead plant carpets anchored to the ground (flooded grasslands), or erect plant stems (swamp vegetation such as cattail, bulrush, or bur-reed) in low-current areas where water depth ranges from 30 cm to 1 m and temperatures are between 7 and 11°C. They systematically avoid inorganic fine-grained substrate with low vegetation cover.
- The cultivation of annual crops reduces the availability of habitats favourable for yellow perch spawning.
- Poor water quality—degraded by sediments, fertilizers, and pesticides—has also led to large losses of submerged macrophyte beds and reduced prey abundance for young yellow perch.
- The productivity of aquatic invertebrates is generally 10 to 100 times higher in the littoral zone compared to the open lake, but this productivity is 2.6 to 10.8 times lower in mowed or tilled fields compared to natural grasslands.
- Reduced connectivity between the lake and the littoral zone due to roads and dams limits fish movement and genetically isolates populations.
- Habitat restoration and development of sustainable agricultural practices in the 0–2 y littoral zone of Lake Saint-Pierre, improved water quality, and higher connectivity between the lake and the littoral zone should be key priorities to support yellow perch populations and more generally the whole biodiversity of Lake Saint-Pierre.

Strategies for floodplain management and restoration

- The major strategy conducted worldwide for the restoration of cultivated floodplains is the exclusion of annual crops and their replacement by extensive grasslands or wetlands together with the re-establishment of natural flow regimes (where floods have been controlled with dams) whereas best agricultural practices (e.g., cover crops, grass strips, riparian buffer zones, nutrient management, organic farming) have generally been applied only to upland areas that do not regularly flood.
- Whether sustainable annual crop production in floodplains is possible must still be investigated.

Effect of current agricultural practices

- Perennial crops are generally more beneficial to water quality than annual crops.
- Some studies have demonstrated higher water infiltration with soybean crops compared to corn, but runoffs are similar.

- Phosphorus loads are generally higher with soybean than corn while nitrate loads are similar despite different levels of fertilization.
- Higher soil porosity and lower soil compaction and crusting with no-till cultivation generally promote water infiltration. No-till significantly reduces runoff by 22% and 27% compared to reduced tillage and moldboard plowing, respectively; residue retention on the soil in no-till systems is more beneficial than residue removal.
- However, other studies have demonstrated non-significant effects of no-till practices on water flows compared to conventional tillage (or even a negative effect of no-till); this has been attributed to higher soil humidity, reduced soil roughness, or reduced cracking of clay soils under no-till.
- Compared to conventional tillage, no-till improves soil structure, organic matter content, water storage, and increases earthworm populations and tile drainage water volume, but also nitrate losses. Controlled drainage systems may be required in no-till fields to prevent excessive nitrate leaching and should be complemented by other practices (e.g., cover crops, reduced fertilizer dose, or split fertilizer applications) to improve soil nitrogen retention and mineralization.
- Reducing tillage may shift weed communities from annual dicots to annual grasses and perennials, and no-till should be complemented with diversified crop rotation to avoid severe weed infestation.
- Reducing fertilizer dose or splitting fertilizer applications may help to reduce nutrient losses to waterbodies. In addition, the weather condition during fertilization as well as fertilizer types strongly impact nutrient leaching.
- Water quality degradation by pesticide residuals in an increasing environmental concern.
- Diversifying crop rotation, leaving crop residue on the ground, and adjusting crop sowing density to promote crop–weed competition as well as mechanical weeding are alternative management practices to support weed control and therefore reduce the need for herbicides.
- In comparison to conventional farming, organic farming is a well-known agriculture system that supports farmland biodiversity and is characterized by higher soil quality and reduced nutrient and pesticide leaching compared to conventional agriculture.
- While the adaptations of current agricultural practices could help to restore Lake Saint-Pierre's littoral zone, they may not be sufficient and should be complemented with additional agroecological practices.

Cover crops

- Cover crops protect the soil from erosion and nutrient loss by runoff and leaching and improve soil quality through their effects on organic matter and biological activity in the soil.
- There are two main types of cropping systems for cover crops:
  - Intercropping system: cover crops are established at sowing or during the growth of the cash crop and then cultivated simultaneously with the cash crop (e.g., ryegrass interseeded at the 4- to 8-leaf stage of corn).
  - Successive cropping system: cover crops are sown right after harvest of the cash crop or during the last growth stages of the cash crop (e.g., tillage radish after cereal harvest, winter rye sown by broadcast before soybean defoliation).
- It is especially important under northern climates with short growing seasons and severe cold that the cover crop be carefully selected to provide adequate soil protection or nutrient uptake during fall and before winter conditions.
- Cover crops belong to three main plant groups—grasses, legumes, and brassicas—that differ in their morphology, environmental tolerance (including tolerance to flood and frost), decomposition rate, and therefore potential use. For example, grasses have lower decomposition rates than legumes, so their residues cover the ground longer; winter annuals and cool-season annuals better suit successive cropping systems; and perennials are better adapted to intercropping systems.
- Among potential fast-growing cold-tolerant plants, winter rye is probably the most reliable grass species. This species also has persistent residues and is a good nitrogen scavenger and soil builder. Ryegrass also seems more flood tolerant than other species; radish is a good nitrogen scavenger and soil builder; and linseed has persistent residues.

- Weed control:

  - Cover crops support weed control through direct competition and allelopathic activity.
  - The efficiency of weed suppression mainly depends on the cover crop biomass.
  - Grass cover crops (rye in particular) and mixtures supress weeds more effectively than legumes alone.

- Soil and water ecosystem services:
  - The extent to which cover crops provide soil and water ecosystem services largely depends on the cover crop species, biomass, decomposition rate, or termination method.
  - Species with high biomass, including rye, promote runoff interception, while species with dense and deep root systems, such as brassicas, favour water infiltration and nutrient retention. Species mixtures may therefore be considered to promote multiple ecosystem services.
  - Non-leguminous cover crops reduce nitrate (NO_3^-) leaching by 53% on average, but the cover crop species (broadleaf non-legumes are more efficient than legumes), planting dates (early planting promotes NO_3^- retention), and higher shoot biomass as well as tillage, precipitation, and soil type all greatly influence the magnitude of this effect.
  - Cold climates could cause phosphorus release from cover crops. Cover crops should thus be selected considering the specific agricultural context.
  - The slower decomposition of grass cover crop residues generally promotes higher soil carbon accumulation than legume cover crops, but mixtures are also generally more beneficial to soil organic carbon accumulation than monospecific crops because of higher biomass production.
  - Increased soil microbial activity under cover crops is generally positively correlated with an increase in soil organic carbon, while changes in soil microbial biomass, microbial community structure, fungal biomass, and fungal hyphal biomass affect soil aggregation.

- Wildlife conservation:
  - Few studies have documented the effects of cover crops on wildlife except for higher abundances of soil invertebrates and earthworms.

- When multiple services must be simultaneously optimized, plant community ecology suggests that the cultivation of plurispecific cover crops is a promising perspective.
- The cultivation of cover crops is complex and must be adapted to specific local constraints to optimize their benefits. Above all, studies showing positive impacts of cover crops on water and soil predominantly refer to non-flooded areas, so it is not clear how flooding can modulate the influence of cover crops.

Grasslands

- Agricultural grasslands are cultivated as perennial forage crops (pasture, hay, silage) with lower fertilizer input compared to annual crops. Grass strips can also be established to reduce sediment and nutrient losses.
- In Québec, 22 species or species groups have been identified as forage plants, including 14 grass species and eight legumes; 20 are perennial species and two are annuals (Italian ryegrass and Japanese millet). These forage plants differ in their morphological characteristics and environmental tolerances.
- Among these plants, two grasses—reed canarygrass and tall fescue—show good to very good tolerance to water-saturated soils or transient flooding.
- Regarding winter survival, timothy grass is considered to be the most frost-tolerant species among the listed forage plants, while alfalfa and orchard grass are the most sensitive to winter conditions.
- Mixtures containing red clover and birdsfoot trefoil are generally better adapted to poorly drained soils than alfalfa-based mixtures.
- For grazing, many grass-based mixtures (e.g., timothy–reed canarygrass, orchard grass–meadow bromegrass) in association with legumes (birdsfoot trefoil or white clover) are recommended in Québec.
- The environmental conditions of the Lake Saint-Pierre littoral zone suggest that reed canarygrass (high flood-tolerance despite slow rate of establishment), timothy (high frost-tolerance), red clover, and birdsfoot trefoil may

be better adapted for cultivation in this environment. In addition, mixtures including three or more species may be more resilient to strong environmental variations and regular natural disturbances.

- Cultivars of reed canarygrass have been selected for their low content of naturally occurring alkaloids. Alkaloid content in reed canarygrass is a highly heritable character that can range from less than 0.01% dry weight to more than 1% with large variations among genotypes, even if environmental variations in light intensity, soil moisture, or fertility often induce changes in alkaloid contents. Alkaloid content in reed canarygrass generally decreases with maturity. Concerning selection for flood tolerance, further investigation could focus on whether hybridization with natural populations, environmental conditions, or molecules other than alkaloids decrease the palatability of forage harvested from agricultural cultivars.

- Soil and water ecosystem services:
    - In the eastern US, perennial pastures compared to conventionally tilled annual crops were found to decrease the proportion of precipitation resulting in water runoff by 38% and soil losses by 92%.
    - Perennial–annual crop rotation and grassland strips reduce runoff and increase water infiltration, and thus trap large amounts of sediments, nitrogen, phosphorus, and residual pesticides. However, several factors influence the magnitude of sediment and nutrient loss reduction by grasslands, including:
        1) Morphology of the grass species, including the root system.
        2) Grass community structure, composition, biomass, and cover.
        3) Grass strip width, proportion, and location in the watershed, i.e.,
            - The optimal width of grass strips for sediment retention has been evaluated at 10 m.
            - The area ratio of grassland strips (ratio of drainage area to filter strip area) is a key factor of sediment trapping efficiency. While many studies are based on area ratios lower than 5:1, guidelines recommend a typical area ratio of 30:1 and a maximum area ratio of 50:1 to 70:1 depending on soil type and rainfall. As for erosion control, modelling approaches found that filter strips covering 10–50% of the drainage area could lead to 55–90% NO_3^- reduction during an average rainfall year. In addition, while NO_3^- losses decreased with increasing area of vegetated strips, these reductions of NO_3^- losses were more pronounced with strip coverages of between 10 and 20% than those between 20 and 50%, suggesting that 20% strip cover is optimal for reducing NO_3^- losses.
            - Grass strips located at footslopes are more effective for sediment and nutrient retention than grass strips located along contours within fields.
            - Grass filters reduce phosphorus loads largely by reducing runoff volume rather than reducing phosphorus concentrations.
            - The diversity and composition of grass strips are important to consider when the reduction of water-soluble herbicides is targeted. Grass strips can also provide efficient filters against insecticide loss (e.g., neonicotinoid).
        4) Forage harvest *versus* grazing: higher grazing intensity can lead to higher runoff, and plant biomass harvest can also limit the efficiency of grasslands in controlling erosion. Nevertheless, regular biomass harvest could help to reduce the risk of sediment and phosphorus accumulation and losses from buffers over the long term.
        5) Soil management.
        6) Natural factors (soil type, hydrology, and even more slope).
    - Soil organic content and microbial activity are also positively influenced by grassland cultivation, with potential indirect benefits on erosion risk, nutrient retention, and annual crop yield.

- Weed control and wildlife conservation:
    - Perennial forage crops provide weed suppression because their dense cover, regular harvesting, and absence of tillage is particularly unfavourable for annual weeds. Diversifying crop rotation by alternating forage and annual crops may therefore support herbicide reduction.

- Perennial crops and grass strips generally promote a greater richness and abundance of arthropods, pollinators, butterflies, and farmland birds compared to annual crops.
- Even though some studies have identified higher phytoplankton, zooplankton, or macroinvertebrate abundance or diversity in wet meadows restored to natural state after agricultural use, these results should be verified in the context of annual crop conversion to perennial crops.

Riparian buffer zones

- The riparian zone is the interface between aquatic and terrestrial ecosystems; riparian buffer zones (RBZ) strictly refer to riparian zones established between streams and arable fields that are meant to provide multiple ecosystem services related to water quality, soil stability, and biodiversity.
- Besides sediment (sand or gravel) bars that can be vegetated or not, three main types of vegetation are often distinguished in the context of restoring riparian buffer strips in agricultural landscapes: riparian forests dominated by trees, riparian shrublands dominated by shrubs, and riparian grasslands dominated by grasses and forbs; plurispecific plant assemblages closer to the native vegetation are most beneficial in terms of ecosystem services.
- A type of RBZ that has proven its efficiency is the 15 to 20 m wide three-zone riparian buffer strip recommended by the USDA, composed of switchgrass, shrubs, and trees arranged in three successive zones from the field to the stream.
- Sediment removal by RBZ can be very efficient, ranging from 21 to 97% for buffer strips 3 to 65 m wide, regardless of vegetation type. Efficiency in sediment removal is affected by buffer width (optimum 10–30 m), slope (optimum 10%), and flow conditions of the water course, with higher flows lowering the effectiveness of the buffer. Herbs are efficient for trapping sediments, reducing sediment loads by up to 95% within a few metres.
- RBZ can remove a large amount of nitrogen (N) in both runoff and subsurface flows, through either the physical removal of organic N, plant uptake, or, in anoxic conditions, the denitrification of soluble N. The efficiency of N removal is affected by subsurface hydrology (e.g., subsurface water flux; slower flow is more efficient), vegetation type (trees and shrubs are usually better), and stream order (low-order streams—i.e., streams located in upstream watershed areas—are better suited for denitrification).
- While denitrification is an important ecosystem service, denitrification taking place in RBZ can also be a source of nitrous oxide (N_2O), which is itself an ecosystem disservice and must be accounted for. Nevertheless, except in very acidic soils, the disadvantage of N_2O production is largely outweighed by the benefits of N removal.
- Phosphorus (P) removal by RBZ, either as particulate or soluble P, can also be very high although variable, ranging from -36% to 89% removal efficiency for total P in cold climates. The efficiency of P removal depends on its form (either particulate or dissolved) and is affected by vegetation type (trees being generally more efficient at removing both particulate and dissolved P) and RBZ management (physical removal of P by plant biomass harvesting is necessary to maintain the efficiency of long-term RBZ P removal). Riparian soils do not tend to become saturated with P, but rather exhibit higher amounts of soluble P, making them prone to leaching.
- Pesticide removal by RBZ can be up to 93% for a 30 m wide buffer, depending on the physiochemical properties of the pesticide: the more tightly the pesticide is bound to the organic carbon, the more likely it is to be removed with sediment. Efficiency can also be hampered by concentrated flow conditions or, in the case of soluble contaminants, by subsurface bypass of the RBZ (e.g., lateral flow, tile drains).
- Riparian buffer zones have the potential of reducing pathogen amounts by 61–94% from field runoff for RBZ widths between 1.5 and 6 m.
- Riparian buffer zones contribute to water temperature regulation in streams, especially during the warmest days of summer, through shading and modification of stream geomorphology. Temperature regulation is affected by vegetation type (trees provide more shade than herbaceous species for streams >2.5 m wide), buffer length and width (the longer and the wider the better), and hydro-geomorphology of the stream (lower width-to-depth ratios and higher proportions of sand in the substrate are associated with cooler temperatures).

- Riparian buffer zones favour soil stability by covering the ground and enhancing soil cohesion with roots. Riparian soil stability is affected by vegetation type, with trees and shrubs being the most beneficial. However, trees are associated with wider streams compared with grasses, forbs, and shrubs, and a shift in vegetation following RBZ restoration could result in a short-term increase in erosion.
- Riparian buffer zones contribute to biodiversity by acting as habitat, refuge, and food source for many species (e.g., macroinvertebrates, birds, fishes); by modifying in-stream or terrestrial habitats for plant and animal species; and by serving as ecological corridors. The extent to which RBZ affect biodiversity is correlated with their width and length (the bigger the area, the better) as well as large-scale watershed effects (local effects of RBZ on biodiversity may be limited by other large-scale or upstream environmental pressures).
- Impacts of forested and herbaceous RBZ on biodiversity are different and complementary: they each support different macroinvertebrate assemblages and serve as refuges for fish by limiting fishing at different moments in the season. It is therefore recommended that a mix of both grassy and wooded RBZ be implemented to maximize habitat heterogeneity and biodiversity.
- Factors that have the most impact on the overall efficiency of RBZ are vegetation type, width, scale of implementation, and the presence of bypasses such as drainage or concentrated flows.
- Studies give evidence for the positive impacts of RBZ on water quality, but it is not clear how flooding can modulate this influence considering that lower slope and flow conditions could limit the effectiveness of the buffer.

Case studies

- Agriculture – water quality policies in member countries of the Organisation for Economic Co-operation and Development:
  - In 2004, OECD listed 364 means of action to reduce non-point pollution; 57% were dedicated to nutrients, 34% to pesticides, and 8% to both these pollutants.
  - The number of actions implemented for water quality vary among OECD countries: there are 15 in France, 14 in the USA, nine in Canada, and two in Japan.
  - The main categories of measures to reduce agriculture-related water quality problems include economic instruments (*stimulation*, often voluntary), environmental rules (*regulation*), and information and awareness campaigns (*persuasion*) applied at various scales (local, watershed, provincial, multi-state).
  - Agro-environmental incentives (through tax returns, investment aids, or, more rarely, cash payments) are frequently used in OECD countries for biodiversity preservation, pollution risk reduction, soil conservation, buffer establishment, or wetland restoration that can directly or indirectly contribute to the improvement of water quality.
  - New actions such as water quality trading systems are becoming increasingly common.
  - Diverse categories of measures are recommended to achieve water quality goals.

- Action program for nitrates (Brittany, France):
  - The European Nitrates Directives was established in 1991 to reduce nitrate water pollution from non-point agricultural sources in the European Union.
  - To limit degradation of water quality and environment health, and hence meet the EU objectives, the Brittany region has established successive action programs.
  - Actions include strict rules for fertilizer application and organic manure storage, cultivation of cover crops, and establishment of buffer zones along rivers.
  - Cover crops are mandatory during the long intercrop season (mid-September to January), during the short intercrop season between oilseed rape harvest and winter cereal (July to October), and after corn harvest (November to January). A list of authorized cover crop species has been provided, and fertilizer and pesticide use is also strictly prohibited.

    - Along rivers, a perennial 5 m wide strip must be planted (10 m wide, in *reinforced action zones*) within which grazing is authorized but not fertilizer application.

  - Natura 2000 network (Europe):
    - Natura 2000 is a European network of core breeding and resting sites for rare and threatened species and of rare natural habitats. It was established in 1992 in response to the Habitats Directive and the Birds Directive adopted earlier.
    - There are 58 habitat types that are considered key farmland habitats because they are dependent on or associated with extensive agricultural practices; these include alpine meadows and pastures, steppic plains, open heathland, and wet grasslands.
    - The EU provides financial incentives and guidelines for the management of farmland habitats listed as Natura 2000 sites, including the recommended mowing period or frequency, grazing intensity, or hydrological regulation.

- The Conservation Reserve Program (USA):
  - The Conservation Reserve Program (CRP) is a cost–share and rental program of the US Department of Agriculture (USDA) that was officially created in 1985 through the Farm Bill policy. Its aim is to promote the conversion of croplands to permanent vegetation cover to reduce land erosion, improve water quality, and conserve wildlife.
  - Precise guidelines, eligibility conditions, and financial incentives were established by the USDA for the 16 conservation practices of this program.
  - For all practices, conservation actions are only eligible for croplands that have been cultivated four out of the six years prior to establishment of the conservation practice.
  - Conservation actions notably include the establishment of permanent introduced or native grasses and legumes in croplands, grassed waterways, contour grass or grass–legume strips, and riparian buffers.

- The Chesapeake Bay Program (Maryland and Virginia, USA):
  - The *2014 Chesapeake Bay Watershed Agreement* identifies six major restoration actions proposed to farmers to reduce sediment and nutrient loads and meet the goals of the US Environmental Protection Agency as outlined in *Chesapeake Bay Total Maximum Daily Loads*, i.e.,1) implementing conservation tillage through no-till or conservation-reduced tillage, 2) cultivating cover crops, 3) establishing forest buffers along the edges of farm fields or along rivers and streams, 4) fencing streamsides to exclude livestock, 5) planning nutrient management to adjust fertilizer amounts and times of application with crop needs, 6) developing manure and poultry litter management systems, including animal waste storage facilities.
  - In addition to financial incentives, the large-scale adoption of conservation practices in farmlands is promoted by the regular publication of precise technical guidelines for each practice by the Chesapeake Bay Program after expert panel evaluation; these are made available to farmers and agronomists.
  - The 25 best management practices for agriculture include:
    - Land retirement or alternative crops to convert cropland into less managed vegetation such as hay or grasses, typically on marginal or highly erodible croplands.
    - Cover crops such as winter or spring cereal and others (forage radish, annual legumes, grasses, annual ryegrass, brassica).
    - Pasture and grazing management practices for improved rotation or prescribed grazing.
    - Stream restoration by natural channel design or legacy sediment removal.
    - Forest and grass buffers.

- The Lake Champlain Basin Program (Vermont and New York, USA; Québec, Canada):
  - The Lake Champlain Basin Program is responsible for implementing the restoration program whose main goal is to reduce phosphorus (priority objective), which exacerbates algal blooms; to reduce toxic contamination; to minimize the risks to humans from water-related health hazards; and to control the

introduction, spread, and impact of non-native nuisance species in order to preserve the integrity of the Lake Champlain ecosystem.
  - Regarding conservation actions for agricultural areas, differentmain tasks are defined including the implementation of Best Management Practices, streambank stabilization, riparian area restoration, fertilizer application reduction, conversion of annual crops to perennial crops in 30% of the flood-prone areas concerned, creation of phosphorus removal facilities in tile drains and agricultural ditches, and technical assistance to farmers.

- The Lake Ontario Atlantic Salmon Restoration Program (Ontario, Canada):
  - In 2006, the Ministry of Natural Resources and Forestry of Ontario in collaboration with more than 30 partners and sponsors launched a 20-year restoration program to bring back wild populations of Atlantic salmon to Lake Ontario.
  - The Lake Ontario Atlantic Salmon Restoration Program includes four main components, i.e., fish production and stocking, water quality and habitat enhancement, outreach and education, and research and monitoring.
  - Water quality and habitat enhancement consists of six main conservation actions: 1) tree planting in riparian areas to stabilize banks and decrease sedimentation and water temperature; 2) debris management to enhance and restore natural flows, clean substrate, and enhance habitat for adult and juvenile fish; 3) bank stabilization projects to minimize erosion and sedimentation of spawning and nursery areas; 4) wetland protection to ensure the high quality and quantity of water; 5) cattle fencing and alternative watering systems to prevent riparian grazing, erosion, and in-stream habitat destruction; 6) modification, by-pass, or removal of online dams and ponds to re-establish natural channels, decrease stream temperatures, and allow fish passage.

- The STRIPS research experiment (Iowa, USA):
  - The “Science-based Trials for Rowcrops Integrated with Prairie Strips” (STRIPS) experiment was established in 2007 by an interdisciplinary team in the USA to identify how the water quality and biodiversity of watersheds undergoing a corn–soybean rotation can be improved through the targeted incorporation of native prairie vegetation.
  - In this study, twelve experimental watersheds (0.4–3.2 ha with 6–10% slope) in corn–soybean rotation were studied. Experimental treatments consisted of strategically placed prairie strips. More precisely, the treatments included 1) 100% row-crop (control), 2) 90% row-crop with 10% footslope prairie strip, 3) 90% row-crop with 10% prairie integrated along contours, and 4) 80% row-crop with 20% prairie integrated along contours. Prairie strips had a minimum width of 4 m but were wider in preferential water runoff areas. The minimum distance between strips was 36 m, which accommodated agricultural operations using standard farming equipment.
  - Farm-level financial models were used to assess the annual establishment, management, and opportunity costs associated with crop production and prairie strips for 2008–2015.
  - Integrating prairie strips into cropland (compared to no strips) led to reduced total water runoff from catchments by 37%, resulting in a 20-fold reduction of sediment loss, a 4.3-fold reduction of phosphorus loss in surface runoff, 3.3-fold reduction of total nitrogen concentration in surface water, and 3.6-fold reduction of total nitrogen concentration in groundwater.
  - The 20% prairie treatment had a small but significantly higher grassland bird abundance, species richness and diversity, and lower dissolved organic carbon (DOC) concentrations in surface runoff compared with the 10% prairie treatment, but differences in total DOC loads were not detected.
  - Agronomic yields and weed cover did not vary on cropped portions of catchments with or without prairie strips. Although the associated losses in net revenues (accounting for property taxes, crop production costs, prairie strip establishment costs, maintenance costs, and crop revenues) did not differ significantly among treatments, the average net revenue was 124 US $\$.ha^{-1}$ lower during corn years and 88 US $\$.ha^{-1}$ lower during soybean years for catchments.

Key research questions

- <u>In relation to landscape management</u>:
  - Which areas of the littoral should be prioritized for restoration, based on hydrological dynamics?
  - Would practices other than perennial crops be sustainable, and which proportion of the landscape could eventually support annual crops?
  - Which landscape characteristics would promote or impede restoration success?
  - How could agroecological practices be practically implemented to favour a wide range of ecosystem services?
  - Should diverse local restoration strategies be proposed to promote landscape diversity?

- <u>In relation to providing ecosystem services</u>:
  - What are the trade-offs and synergies between the ecosystem services of interest?
  - Which restoration strategies could benefit multiple ecosystem services?
  - What are the relationships linking taxonomic or functional species diversity to ecosystem services?

- <u>In relation to the management of cover crops</u>:
  - Which cover crop species could survive and establish under floodplain conditions?
  - Could multiple ecosystem services be optimized across seasons using cover crop mixtures composed of species with distinct environmental tolerances and traits?
  - Which adapted agricultural management strategy (sowing period, fertilization dose, cash crop type, termination method) could allow for cover crop cultivation without negatively impacting crop yield?
  - What is the influence of cover crops on water quality (including both nutrient retention and potential release), soil physiochemistry, and weed control in flooded environments?
  - What are the benefits of cover crops on aquatic biodiversity, especially for yellow perch spawning or zooplankton productivity?

- <u>In relation to management of perennial crops and grass strips</u>:
  - Which species or species mix could be cultivated under cold and flooded conditions that also provides acceptable forage quality?
  - Which width, location, or proportion of a watershed would optimize the benefits of grass strips or perennial crops on water quality, and for which associated agricultural management and use (forage harvest, grazing, or no management)?
  - What are the direct and indirect benefits of perennial crops for aquatic or terrestrial wildlife?

- <u>In relation to riparian buffer zone management</u>:
  - How would the previously observed benefits of riparian buffer zones be modulated by recurrent flooding?
  - Which species and mode of introduction (seeds, rhizomes, saplings) would favour vegetation establishment despite regular flooding?
  - What are the impacts of riparian buffer zones on biodiversity, especially on yellow perch?
  - How should riparian zones be restored so as not to impede hydrological connectivity and fish movements?

- <u>In relation to the complementarity between practices</u>:
  - What are the trade-offs and synergies between agroecological practices?
  - Could different restoration alternatives be proposed to achieve a specific goal?

- <u>In relation to other potential beneficial practices</u>:
  - Could the cultivation of new crop species (e.g., buckwheat, wild rice, medicinal herbs, berries) with sustainable impacts be considered?

- Should additional actions also be mandatory in the upland areas surrounding the littoral zones, and if so, which ones (sediment retention basins, enhanced riverbeds, hydrological management)?

- In relation to socio-economic aspects:
  - What are the costs and benefits of agroecological practices, including indirect ones?
  - What parameters favour the adoption of agroecological practices by farmers?
  - Which financial or regulatory incentives could promote the adoption of agroecological practices?
  - How can people be encouraged to support and become engaged in the project?

- In relation to methodological issues:
  - How can the effects of agroecological practices on water quality during flooding be accurately evaluated when waterbodies mix together, and should an experimental watershed approach be considered in addition to the classical lysimeter approach during non-flooding periods?
  - How can inter-seasonal variations in the provision of ecosystem services be measured or accounted for (e.g., nutrient retention versus release in relation to climate)?
  - Could hydrological modelling help to define the location or width of the experimental treatments to test?
  - How can the results of local experiments be upscaled to the whole littoral zone?

- In relation to long-term management:
  - How would ecosystem services vary though time, and which operations could help to maintain them over the long term?
  - Which agroecological practices could endure long-term environmental shifts such as climate change or resist biological invasions?