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Research article

A decision-making framework for evaluating environmental tradeoffs in enhancing ecosystem services across complex agricultural landscapes

Juan S. Acero Triana [a], Maria L. Chu [b,*], Nathan J. Shipley [c], Carena J. van Riper [c], William P. Stewart [d], Cory D. Suski [c]

[a] Department of Environmental Sciences, University of California, Geology Building, 900 University Avenue, Riverside, CA, 92521, USA
[b] Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, 1304 West Pennsylvania Avenue, Urbana, IL, 61801, USA
[c] Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, 1102 South Goodwin Ave, Urbana, IL, 61801, USA
[d] Department of Recreation, Sport and Tourism, University of Illinois at Urbana-Champaign, 1206 S 4th St, Champaign, IL, 61820, USA

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ABSTRACT

Decision-making processes to ensure sustainability of complex agro-ecosystems must simultaneously accommodate production goals, environmental soundness, and social relevancy. This means that besides environmental indicators and human activities, stakeholders' perceptions need to be considered in the decision-making process to enable the adoption of mitigation practices. Thus, the decision-making process equates to a multi-criteria and multi-objective problem, requiring additional tools and methods to analyze the possible tradeoffs among decision alternatives based on social acceptability. This study was aimed at establishing a decision support system that integrates hydro-ecologic models and socio-cultural perspectives to identify and assess feasible land management alternatives that can enhance the Kaskaskia River Watershed (KRW) ecosystem services in Illinois (USA). The Soil and Water Assessment Tool (SWAT) was used to simulate the spatio-temporal response of nine environmental predictors to four major management alternatives (crop rotation, cover cropping, reduced tillage, modified fertilizer application) based on stakeholder acceptability and environmental soundness, under 32 distinct climate projections. The stochastic multicriteria acceptability analysis (SMAA) was then applied to classify the management alternatives from the least to the most efficient based on three preference schemes: no preference, expert stakeholders' preference, and non-expert stakeholders' preference. Results showed that preference information on watershed ecosystem services is crucial to guide the decision-making process when a broad spectrum of criteria is considered to assess the management alternatives' systemic response. The disparity between expert and non-expert stakeholders' preferences showed different rankings of alternatives across several subcatchments, where the two-year corn one-year soybean rotation scheme was expected to offer the best management alternative to ensure a sustainable agro-production system in the highly cultivated subcatchments of the KRW. In contrast, non-conventional tillage practices were expected to contravene agricultural production, and therefore should be discarded unless combined with complementary measures. This study will enable stakeholders to identify the most suitable management practices to adapt to natural and anthropogenic changes and encourage engagement between government institutions and local communities (multi-stakeholder consensus) to provide a better platform for decision-making.

1. Introduction

The interactions between humans and the environment are driven by the benefits or services that ecosystems provide for the well-being of the species, including shelter, food, recreation, or water supply (Millenium Ecosystem Assessment, 2005). Human settlements have predominantly emerged alongside rivers and lakes or in areas overlaying major aquifers to use available water resources for domestic and agricultural supply, transport, trade, and recreation (Fang and Jawitz, 2019). However, the expansion of the agricultural frontier to feed an increasing global population, and the intensification of the economic activities due to industrialization and globalization, have led to competition for water and land resources likened to a pendulum swing that moves between human productivity and environmental restoration (Kandasamy et al., 2014;

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* Corresponding author.
E-mail address: mlchu@illinois.edu (M.L. Chu).

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Van Emmerik et al., 2014). In this context, human-environment interactions behave as a coupled system with a defined self-organizing structure that regulates human impacts through awareness, technological breakthroughs, and migratory flows as responses to environmental degradation (Di Baldassarre et al., 2015; Kandasamy et al., 2014; Troy et al., 2015). Therefore, the assessment of the state and spatiotemporal evolution of contemporary hydro-ecologic systems can be conceptualized as a system that includes human components (Sivapalan et al., 2012; Xu et al., 2018) rather than positioning humans as an external disturbing agent (Troy et al., 2015). This means that both human activities and preferences for the future need to be considered in decision-making processes for land management.

Scenario development is an efficient way of evaluating decision alternatives to balance the tradeoffs inherent in the human-environment interactions (Xu et al., 2018). It provides an opportunity for understanding how local and global stressors influence a set of plausible future conditions aimed at formulating more sustainable strategies to reduce environmental degradation (Swart et al., 2004). Scenario planning thus can account for important uncertainties in the system, which supports greater resilience in decision-making (Peterson et al., 2003). However, decision-making processes represent a challenge in and of themselves. Even though scenario-based analysis can provide decision-makers with information about plausible states of hydro-ecologic systems under certain conditions, production goals, environmental soundness, and social relevancy need to be simultaneously considered. For instance, in complex agro-production systems, government institutions may face a dilemma as some farmers are forced to increase crop yields to make a living, while other stakeholders such as environmentalists may prefer the recovery and protection of native ecosystems. Moreover, ecosystem services in such agro-production systems are widely diverse. They provide direct products from nature (e.g., drinking water, timber, gas), regulate natural phenomena (e.g., pollination, carbon storage), contribute to the development and cultural advancement of people (e.g., recreational opportunities, aesthetics), and support processes that sustain the basic forms of life (i.e., photosynthesis, soil genesis, water cycle) (Collins and Larry, 2008; Millenium Ecosystem Assessment, 2005). In this sense, the ecosystem services of a particular region may have different degrees of importance across stakeholder groups. Furthermore, the management alternatives designed to enhance a particular ecosystem service can translate into the degradation of another (e.g., increasing agricultural area can remove vegetation that can lead to sedimentation and increased runoff into streams). Therefore, the decision-making process equates to a multi-criteria and multi-objective problem, requiring additional tools and methods to analyze the possible tradeoffs among decision alternatives.

This research developed a decision-making framework using multi-criteria decision analysis (MCDA) and impact projections of a diverse set of stressors, that span the socio-cultural and environmental dimensions (e.g., climate, management, social expectations), on agro-ecosystems at the watershed scale. The framework was applied to the Kaskaskia River Watershed (KRW) in Illinois, USA, to define the environmental tradeoffs in implementing distinct management alternatives intended to enhance ecosystem services in the watershed. The KRW region provides a vast number of ecosystem services to those who live in the region, but also faces environmental challenges in light of its highly cultivated landscape and controlled flow regime. Additionally, there is strong governance structure and a high level of social organization facilitated by the Kaskaskia Watershed Association (KWA). This organization is focused on balancing water use conflicts and population pressures to protect and restore the native ecosystems (Cooperative Conservation America, 2017). Moreover, landowner and community-based research has been conducted in recent years to provide insights on public opinions and preferences concerning ecosystem services provision across the KRW (Brinkman et al., 2012; Shipley et al., 2020).

The objective of this study was to establish a decision support system that integrates results from hydro-ecologic models and socio-cultural perspectives to assess management alternatives aimed at enhancing the ecosystem services of the KRW. This study was specifically geared to (1) identify the potential surrogate variables for the provisioning, regulating, cultural, and supporting ecosystem services of the KRW; (2) understand stakeholders' preferences for the aforementioned ecosystem

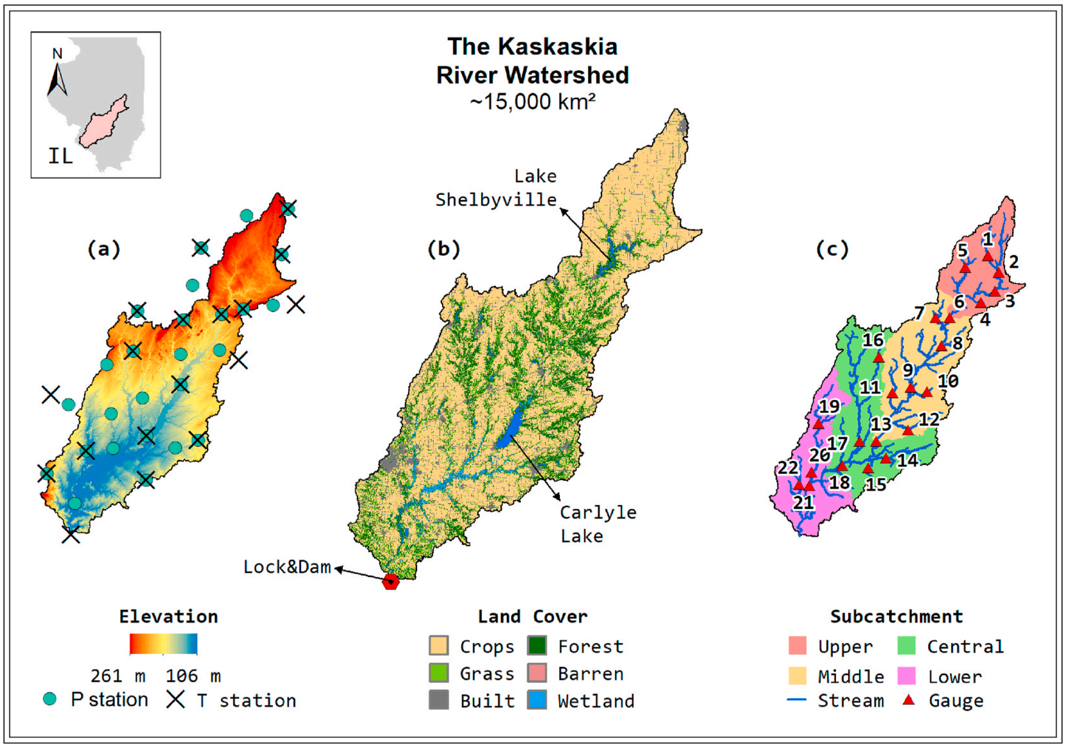


Fig. 1. Main features of the Kaskaskia River Watershed. (a) Terrain elevation and distribution of precipitation and temperature stations; (b) land cover and location of main reservoirs and lock and dam; (c) KRW subcatchments and location of stream gauges.

services; and (3) develop a decision support system using stochastic multicriteria acceptability analysis (SMAA) to rank the conservation practices from the most to the least effective in balancing the tradeoffs between enhancing agricultural production and reducing environmental degradation considering the uncertainty involved in all these processes. Results from this study were developed to enhance stakeholder understanding of environmental issues and be better positioned to make sound decisions and policies that promote a sustainable agro-production system.

2. Materials and methods

2.1. Hydrologic model

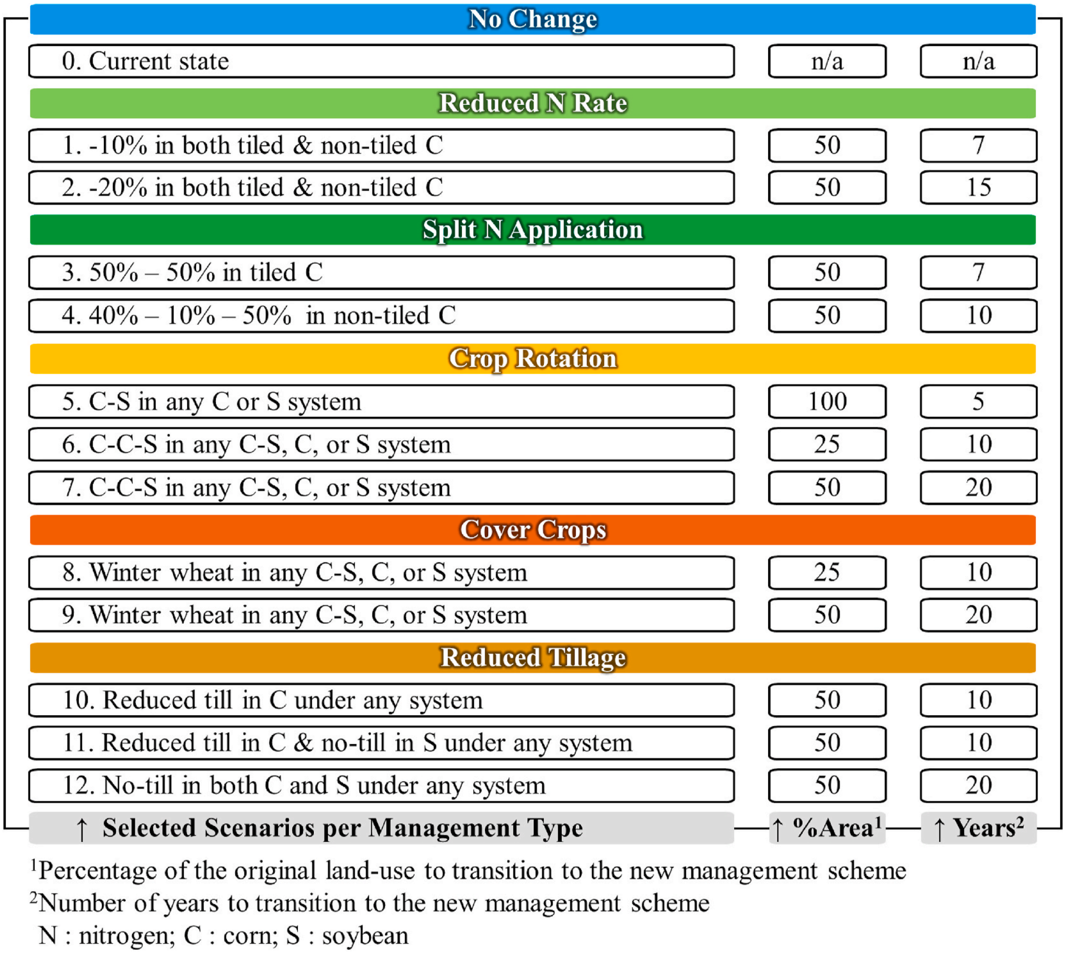
The KRW has experienced accelerated fragmentation of its ecosystems since the early 1700's due to human intervention (Southwestern Illinois, 2002). This environmental degradation has resulted in the conversion of the original cover (i.e., tallgrass prairies, wetlands, and bottomland forest) into row crops and built areas in more than 70% of the watershed (USACE, 2017; USDA, 2016). Additionally, three structures developed in the 1960s (Lake Shelbyville, Carlyle Lake, and Jerry F. Costello Lock and Dam; Fig. 1b) regulate the flow of the main stem of the Kaskaskia River, providing flood protection, navigability, recreation spaces, and water supply to local communities.

Being the second largest watershed in Illinois (~15,000 km^2), the KRW plays a key role in state initiatives to formulate and implement strategies to reduce, mitigate, and control its nutrient and sediment loadings to the Mississippi River and the Gulf of Mexico. Consequently, in the last decade the KRW has been considered one of the target watersheds of the Conservation Reserve Enhancement Program (CREP) and the Nutrient Loss Reduction Strategy (NLRS). In the long-term, these programs aim at restoring and protecting 94,000 ha of environmentally sensitive lands and the reduction of 45% of the nitrate and total phosphorus loads (IDNR, 2017; IEPA, 2015).

To quantify the impacts of future climate and the potential mitigation effects of distinct land-management practices across the KRW, a watershed modeling framework was developed using the Soil and Water Assessment Tool (SWAT), which enabled the simulation of complex ecosystems in heavily cultivated landscapes. In this model the spatial heterogeneity of the watershed was described using 7739 HRUs clustered in 175 sub-basins, each of which allocated one stream or river segment. A significant effort was made towards the implementation of most of the management attributes of the watershed. These included the implementation of long-term rotation schemes identified from refined satellite images (USDA, 2016), fertilizer application, tillage practices, and subsurface tile drainage in the upper subcatchment based on previous study maps (Harmeson et al., 1971; USDA-NRCS, 2009). Moreover, Lake Shelbyville, Carlyle Lake, and the additional five minor reservoirs of the KRW were simulated following the guidelines and constraints formulated by research and government institutions (Illinois State Water Survey, 1975; USACE, 2016a; 2016b). The model was calibrated and successfully validated for the 1980–2017 period against historic records at 22 streamflow gauging stations and seven nitrate-nitrogen, three total suspended sediment, and 10 dissolved oxygen sampling points (Fig. 1 and A.1). This modeling effort was expected to provide a robust and reliable framework to evaluate the interactions within hydrological processes and anthropogenic stressors. Also, it provided a vast set of environmental predictors (e.g., streamflow,

Table 1

Selected land-use scenarios to mitigate future threats in the KRW.



↑ Selected Scenarios per Management Type	↑ %Area[1]	↑ Years[2]
No Change		
0. Current state	n/a	n/a
Reduced N Rate		
1. -10% in both tiled & non-tiled C	50	7
2. -20% in both tiled & non-tiled C	50	15
Split N Application		
3. 50% – 50% in tiled C	50	7
4. 40% – 10% – 50% in non-tiled C	50	10
Crop Rotation		
5. C-S in any C or S system	100	5
6. C-C-S in any C-S, C, or S system	25	10
7. C-C-S in any C-S, C, or S system	50	20
Cover Crops		
8. Winter wheat in any C-S, C, or S system	25	10
9. Winter wheat in any C-S, C, or S system	50	20
Reduced Tillage		
10. Reduced till in C under any system	50	10
11. Reduced till in C & no-till in S under any system	50	10
12. No-till in both C and S under any system	50	20

[1] Percentage of the original land-use to transition to the new management scheme

[2] Number of years to transition to the new management scheme

N : nitrogen; C : corn; S : soybean

sediment and nitrate loads, and crop yields) that may span the distinct ecosystem services of the KRW and the capability to project their future possible state under different climate and land management scenarios.

A scenario-based assessment was employed to project the response of the KRW to selected management alternatives and future climate. The management alternatives were formulated crossing information from expert opinion (Czapar, pers. comm., December 4, 2019; Schaefer, pers. comm., April 18, 2019), state agency reports (IDNR, 2017; IEPA, 2015; IEPA, IDOA, University of Illinois Extension, 2019), and stakeholder input collected from two phases of stakeholder engagement including 1) a Delphi study in 2018 with experts from across the KRW (Shipley et al., 2020); and 2) a series of focus groups conducted in 2019 with the general population, including both experts and non-experts (Chuang et al., 2019). Four major non-structural management practices were identified as the most feasible in terms of stakeholder acceptability and environmental soundness, to ensure a sustainable and resilient agro-production in the watershed: crop rotation, cover cropping, non-conventional tillage, and modified fertilizer application. These four alternatives were implemented in 13 land-management scenarios using a random spatial distribution across the KRW and different linear transition periods starting in 2020 (Table 1). To account for climate-driven uncertainties in the hydro-ecologic system, each of these management scenarios was simulated using a 32-model ensemble downscaled from coarse atmosphere-ocean general circulation models (AOGCMs) produced by the CMIP5 (Bureau of Reclamation, 2016; Meeh and Bony, 2011). Specifically, the highest greenhouse gas emission scenario (RCP8.5) was used in this study to depict the most unfavorable conditions for the watershed in terms of daily precipitation and daily extreme temperatures available until the end of the century at a spatial resolution of 1/16° latitude-longitude.

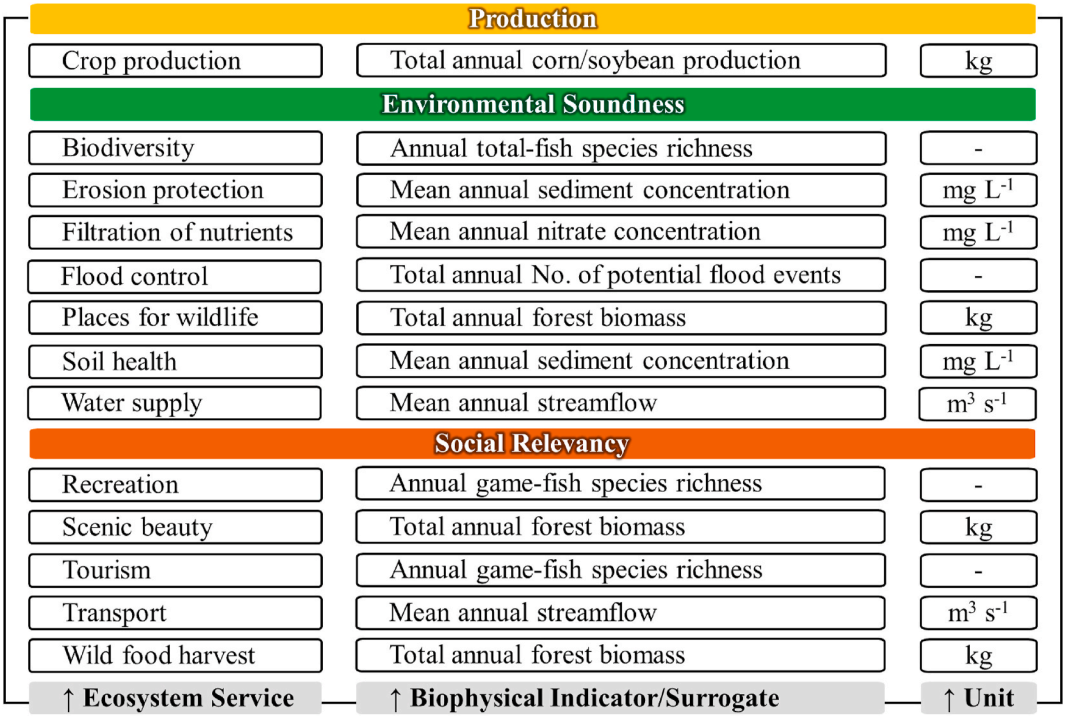
2.2. Ecosystem services assessment

The land-management scenarios developed in this study were designed to enhance the ecosystem services of the KRW associated with three main categories, namely production, environmental soundness, and social relevancy, the latter being crucial in the successful adoption of management alternatives. Shipley et al. (2020) conducted a Delphi study with the stakeholders of the KRW that identified 34 ecosystem services associated with four major landscapes: (1) agricultural lands; (2) water bodies; (3) built areas; and (4) forest lands. This study was followed by four focus group discussions (Chuang et al., 2019) that organized these ecosystem services into 18 unique categories for the entire watershed. Thirteen (13) of these categories were assigned their corresponding biophysical indicators or surrogate variables in the SWAT outputs (Table 2) that may serve as predictors of their future state. The remaining five ecosystem services (i.e., income from non-agricultural products, places for social interaction, commerce, learning, and farming lifestyle) were not considered due to the lack of equivalent hydro-ecologic variables to represent them.

The ecosystem services related to production and environmental soundness were assessed based on the model projections of hydro-ecologic variables on an annual basis. Due to the complexity of quantifying some of the ecosystem services associated with social relevancy (i.e., cultural/aesthetic), they were described by surrogate variables generated by SWAT (Table 2). Thus, crop production, filtration of nutrients, biodiversity, and flood control were described using projections of corn and soybean production, nitrate concentrations, total-fish species richness, and number of potential flood events (Table 2), respectively. The latter corresponded to the number of events in a year in which the outflow from the major reservoirs exceeded their non-damaging release threshold, being equal to 50.97 m3 s^{-1} for Lake Shelbyville and 113.27 m3 s^{-1} for Carlyle Lake (Illinois State Water Survey, 1975). On the other hand, recreation and tourism were jointly evaluated in terms of game-fish species richness assuming that fishing is the principal tourist attraction in the KRW. Similarly, erosion protection and soil health, transport and water supply, and scenic beauty, places for wildlife, and wild food harvest, were jointly evaluated in terms of sediment concentrations, streamflow, and forest biomass, respectively. The aforementioned ecosystem services disposed in dyads or triads obeyed the capability of certain biophysical indicators or surrogates to span the state of several ecosystem services with related characteristics.

Table 2

Ecosystem services evaluated for the KRW and their respective biophysical indicators or surrogate variables computed from the SWAT outputs.



↑ Ecosystem Service	↑ Biophysical Indicator/Surrogate	↑ Unit
Production		
Crop production	Total annual corn/soybean production	kg
Environmental Soundness		
Biodiversity	Annual total-fish species richness	-
Erosion protection	Mean annual sediment concentration	mg L^{-1}
Filtration of nutrients	Mean annual nitrate concentration	mg L^{-1}
Flood control	Total annual No. of potential flood events	-
Places for wildlife	Total annual forest biomass	kg
Soil health	Mean annual sediment concentration	mg L^{-1}
Water supply	Mean annual streamflow	m^3 s^{-1}
Social Relevancy		
Recreation	Annual game-fish species richness	-
Scenic beauty	Total annual forest biomass	kg
Tourism	Annual game-fish species richness	-
Transport	Mean annual streamflow	m^3 s^{-1}
Wild food harvest	Total annual forest biomass	kg

This also enabled the avoidance of additional bias in the decision-making framework due to duplicate data.

Annual projections of total- and game-fish species richness were obtained using records of number of individuals captured per species per sample. A multiple linear regression (MLR) model was used for the former and a generalized additive model (GAM) for the latter, on SWAT-generated environmental predictors such as streamflow, water temperature and concentrations of sediment, nitrate, and dissolved oxygen. The fish data utilized in this study was collected on a non-continuous basis at 222 sites across the KRW by the Illinois Department of Natural Resources Division of Fisheries and provided by the Illinois Natural History Survey with support from the U.S. Fish and Wildlife Service (Federal Aid Project F-69-R to J.A. Stein).

2.3. Decision support system

The final goal of this research was to develop a decision support system that enables decision makers to evaluate the tradeoffs of adopting new land-management practices and determine their feasibility. The decision support process must account for both scientific findings and stakeholders preferences (Lahdelma et al., 1998; Linkov et al., 2006) as part of its feasibility for implementation by local communities.

The MCDA emerged as a suitable strategy to rank decision alternatives in land-use allocation problems, where the enhancement of certain ecosystem services may conflict with social expectations and/or other ecosystem services (Kaim et al., 2018; Linhoss et al., 2013). MCDA techniques allow users to consider multiple decision objectives for evaluation in terms of physical, social, and economic criteria. Consequently, the environmental impact assessment of land-management scenarios under future climate variability is suited to the use of MCDA because of the diverse physical processes, ecosystem services, and stakeholders involved.

In this study, the stochastic multicriteria acceptability analysis method (SMAA), which is distinguished from all the MCDA methods for dealing with problems that involved uncertain criteria values and/or incomplete preference information (Pelissari et al., 2020), was used. This method considers a set of alternatives that are evaluated on the basis of a set of criteria, which can be constrained through a weight vector with preference information. In this context, the alternatives are the elements to compare (e.g., management actions to improve water quality), while the criteria are the attributes on which the comparison is based (e.g., nutrient and sediment concentration). Moreover, the uncertain or incomplete information can be represented as stochastic variables in terms of discrete values, uniform intervals, or probability distributions (e.g., Gaussian, log-normal, beta).

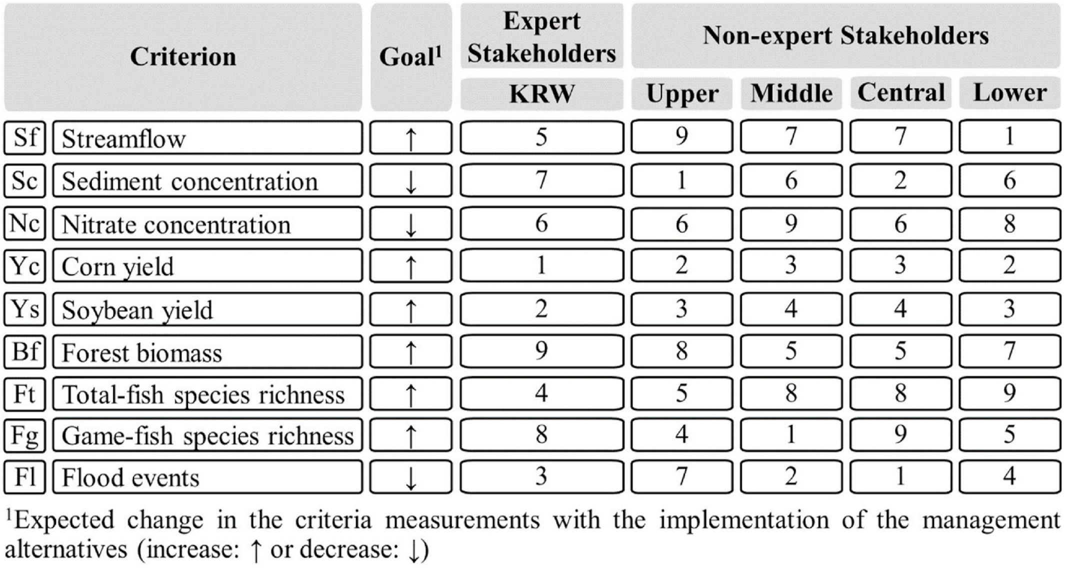
Specifically, we used SMAA-2 (Lahdelma and Salminen, 2001), which unlike the original Lahdelma et al. (1998)'s SMAA methodology, provides information about the alternatives for each possible rank (Lahdelma and Salminen, 2001; Tervonen, 2014). To rank the set of alternatives, SMAA-2 uses 10,000 Monte Carlo simulations to compute descriptive measures based on multidimensional integrals over stochastic parameter spaces. Three descriptive measures are usually employed in the SMAA-2 algorithms. The first and most important measure is called the rank acceptability index (RAI), which describes the probability of an alternative to be the best ranked in a given position, where zero indicates that the alternative is inefficient (i.e., never considered the best) with respect to the assumed preferences (Lahdelma and Salminen, 2001; Tervonen and Figueira, 2008). Hence, it can be used for classifying the alternatives from the least to the most acceptable ones. It is important to note that the RAI values must be re-estimated if the set of alternatives is modified. The second measure, known as the central weight vector, represents the expected center of gravity of all possible weight vectors that rank the alternative at the first position (Tervonen et al., 2011). It is usually applied from an inverse approach to determine which alternatives are more relevant when preference information is missing (Tervonen and Figueira, 2008). Consequently, central weight vectors can be used to assess the impact of each alternative on the criteria set. The confidence factor (CF) corresponds to the third measure and describes whether the provided criteria data are sufficiently accurate to make an informed decision (Lahdelma and Salminen, 2006; Tervonen, 2014). It is expressed in terms of the probability of an alternative to obtain the first rank when the preferences are expressed by its central weight vector (Tervonen et al., 2011). Thus, if the problem is aimed at choosing an alternative to implement, the ones with low-confidence factors should be discarded. It is important to note that a small confidence factor along with a small acceptability index indicates that the provided information is not sufficiently reliable to support a given alternative even when the central weight vector is used (Lahdelma and Salminen, 2001).

The decision support system for the KRW was structured using the SMAA-2 algorithm implemented in the JSMAA software (Tervonen, 2014). The 13 land-management scenarios proposed to mitigate the agricultural intensification impacts (Table 1) were set as the problem alternatives, while the biophysical indicators and surrogate variables associated with production, environmental soundness, and cultural services (e.g., crop production, forest biomass, flood events, etc.) served as the criteria. The criteria measurements were set as discrete distributions constructed from the relative frequency histograms for the decadal percentage changes of each criterion from the baseline period, considering all the values of the systematic response to the 32 climate projections. This analysis was performed separately for the 2040s and 2060s at each of the subcatchments present in the KRW (Fig. 1c) to evaluate spatio-temporal change patterns across the watershed. On the other hand, three preference schemes were employed to identify the most efficient alternatives. Preferences are a set of constraints for the weight spaces, which can either enhance or diminish the impacts of the criteria to depict a differentiated level of importance towards each of them. For instance, in a three-criteria problem with preference information setting the third criterion as the most important and the first as the least (i.e., $c_3 > c_2 > c_1$), the differences in the measurements for c_3 among the problem alternatives would be more relevant for the ranking than those for c_2 and c_1. For the first scheme, no-preference information was provided to analyze the suitability of the alternatives assuming that all criteria were equally important.

For the second and third schemes, the level of importance placed on ecosystem services by stakeholders during the Delphi study (Shipley et al., 2020) and series of focus groups (Chuang et al., 2019), respectively, were treated as ordinal preference information. In the Delphi study, we purposively sampled representatives from key organizations dealing with issues across the KRW including tourism, economic development, and planning. Several example organizations include the US Army Corps of Engineers, Illinois Department of Natural Resources, Natural Resources Conservation Services, and Heartlands Conservancy, among others (Shipley et al., 2020). In the series of focus groups, general advertisements were circulated across the watershed to recruit a broad swath of representatives including expert farmers and general residents who were interested in expressing concerns about potential impacts from policy change (Chuang et al., 2019). Consequently, the second scheme provided the same preference information for the entire watershed, while the third considered specific preference information for each of the four subcatchments (Table 2; Fig. 1c). This enabled understanding the tradeoffs between maximizing ecosystem services and minimizing environmental degradation across the watershed and its prevalence over time. The levels of importance reported by Shipley et al. (2020) and Chuang et al. (2019) were averaged for those ecosystem services that were spanned by a single biophysical indicator or surrogate variable. The levels were described by numbers from 1 to 8 with 1 representing the highest level of importance (Table 3).

The preferences of non-expert stakeholders toward the ecosystem services in the KRW significantly differed from those set by the expert stakeholders (Table 3). While the latter set crop production as the top priority across the entire watershed, non-expert stakeholders prioritized

Table 3
Ordinal weighting schemes for the criteria used in the SMAA-2 to describe the stakeholders' preferences towards the KRW ecosystem services.



Criterion		Goal[1]	Expert Stakeholders	Non-expert Stakeholders			
			KRW	Upper	Middle	Central	Lower
Sf	Streamflow	↑	5	9	7	7	1
Sc	Sediment concentration	↓	7	1	6	2	6
Nc	Nitrate concentration	↓	6	6	9	6	8
Yc	Corn yield	↑	1	2	3	3	2
Ys	Soybean yield	↑	2	3	4	4	3
Bf	Forest biomass	↑	9	8	5	5	7
Ft	Total-fish species richness	↑	4	5	8	8	9
Fg	Game-fish species richness	↑	8	4	1	9	5
Fl	Flood events	↓	3	7	2	1	4

[1] Expected change in the criteria measurements with the implementation of the management alternatives (increase: ↑ or decrease: ↓)

soil health and erosion protection in the upper, tourism and recreation in the middle, flood control in the central, and transport and water supply in the lower subcatchment. It is also worth mentioning that crop production was ranked in the second and third positions in the upper and lower subcatchments, while third and fourth in their middle and central counterparts. Moreover, the filtration of nutrients was lowly ranked (6–9) by the stakeholders across the entire watershed. Similarly, biodiversity appeared to be relatively important only in the upper subcatchment (rank 5) because, in the rest of the watershed, it was ranked the lowest. All this heterogeneity associated with the social expectations indicated the complexities that decision-making faces in land-use allocation problems, as well as the importance of evaluating management alternatives under different preference information schemes. This can help to identify information gaps within government institutions, decision makers, and local communities.

3. Results and discussion

This study developed a structured decision-support system based on the SMAA-2 method and social expectations to rank the efficiency of a set of 13 land-management alternatives and ensure a more sustainable and resilient agro-production system across the KRW under changing climate scenarios. For each preference scheme, the RAI was determined and plotted using 3D bar graphs where the height and color of the bars represent the probability of each management alternative associated with a given rank. These probabilities were further expressed in cumulative values and depicted in heat maps to assess probability gradients across the ranking order for each alternative. Additionally, we plotted the central weight vectors against the environmental predictors to visualize tradeoffs within the criteria and alternatives, and to determine which of the prior provide more support to the alternatives to be the first ranked. For the sake of visualization, subcatchments with similar results were jointly evaluated.

3.1. *No-preference scheme*

In a no-preference scheme, all the 13 management alternatives (Table 1) were evaluated without considering social expectations and hence, were equally important in the SMAA.

From them, the scenarios intended to reduce the application rate of nitrogen fertilizer by 10% and 20% (scenarios 1 and 2; Table 1) were discarded from the analysis because they did not show any significant differences from scenario 0 (no action). Despite these scenarios being able to reduce nitrate concentrations across the KRW, their impacts on other ecosystem services were limited and therefore the criteria measurements were not significant for the decision-making process to differentiate them from the no-action alternative.

3.1.1. *Upper and middle subcatchments*

In the upper and middle subcatchments, the SMAA under the no-preference scheme showed similar RAI values (8%–16%) for scenarios 00 to 09 from rank one to eight (Fig. 2a) in both decades evaluated (2040s and 2060s). This was because the overall impacts of these management alternatives were similar and hence, equally likely to be ranked in any of the first eight positions (Fig. 2c). On the contrary, scenarios 10 to 12 (Table 1), associated with non-conventional tillage practices, reported the lowest RAI values (1%–9%) over the first six ranks and the highest (up to 28%) over the last three (Fig. 2a). Accordingly, these management alternatives may be the least efficient in balancing the tradeoffs between agricultural intensification and environmental impact reduction. The CF values, on the other hand, were slightly higher for the scenarios implementing the C–C–S rotation (i.e., Sc06 and Sc07, Tables 1 and A1) and the nitrogen split application of 40%–10%–50% (i.e., Sc04, Tables 1 and A1) in the upper and middle subcatchments, respectively. Although this outcome provided more confidence to consider the aforementioned management alternatives as the first ranked, the differences within the CF values (0.10–0.22; Table A1) for most of the alternatives were not significant. This implies the complexity of the tradeoffs is high given the criteria used to evaluate the alternatives and would require further preference information to make appropriate decisions.

3.1.2. *Central and lower subcatchments*

For the central and lower subcatchments, scenario 00 (no-action) seemed to be the most likely alternative to be ranked first (13%–20%) and second (13%–15%) in both the 2040s and 2060s, while scenarios 03 to 09 (split N application, crop rotation, and cover cropping; Table 1), as observed for the upper subcatchments, had a similar probability of being

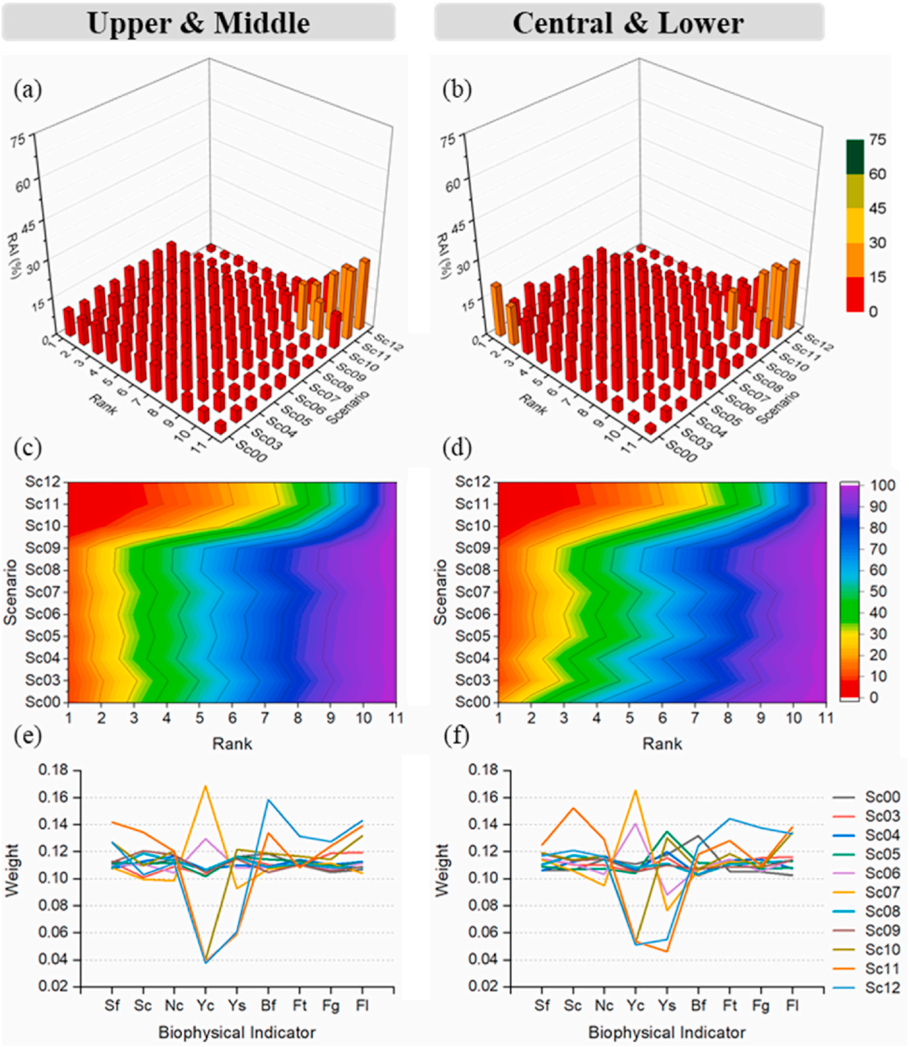


Fig. 2. Descriptive measures for the SMAA under the no-preference scheme. (a–b) RAI (%); (c–d) cumulative RAI (%); and (e–f) central weight vectors in the upper & middle and central & lower subcatchments, respectively.

ranked third to eighth (6%–13%; Fig. 2b and d). Similarly, scenarios 10 to 12 (non-conventional tillage; Table 1) were again in the last three ranks, showing a tendency across the entire watershed. The CF for these subcatchments was up to 0.26 (Table A1) but, compared to their upper and middle counterparts, the CF for the first ranked alternative (i.e., scenario 00) was 1.5 times greater than that with the second highest CF (scenario 04). Analogous to the RAI, the CF leaned towards the no-action alternative (scenario 00) as the most likely solution for the SMAA system. Thus, it appears that the management alternatives evaluated for the KRW may not be relevant for the lower subcatchments under the given preference scheme if considered individually.

3.1.3. Central weight vectors

In the absence of preference information, it is also important to evaluate the patterns described by the weight vectors of each management alternative to determine which criteria are explaining most of the variability affecting the decision-making process. The weight vectors in Fig. 2e and f showed the complex tradeoffs within the evaluation criteria, with the crop yields (Yc and Ys), sediment concentration (Sc), forest biomass (Bf), game-fish species richness (Fg), and flood events (Fl) being the most varying criteria across the alternatives and subcatchments. Recall that the weight vectors represent the average weight of each criteria supporting the ranking of a given alternative at the first position. Accordingly, note that, for the alternatives that appeared to be the least efficient (scenarios 10 to 12; non-conventional tillage; Table 1), the weights for the crop production criteria (Yc and Ys) were significantly smaller (0.04–0.08) relative to those for the remaining criteria (0.10–0.17; Fig. 2c and d). On the contrary, scenarios 06 and 07 (Table 1), implementing a C–C–S rotation scheme seemed to satisfy the production goals without significantly affecting the remaining criteria. However, we believe that preference information may be required to guarantee an informed decision as neither the RAI nor the CF fully validated the implementation of any of the management alternatives evaluated and stakeholders' preferences have not been considered yet to constrain the decision-making process. It is also important to note that the decision-making framework with no-preference did not considerably changed from the 2040s to the 2060s, indicating that despite the warming temperature trends, the effect of the management alternatives remained at the same relevance level.

3.2. Expert stakeholders' preferences for the future

In accordance with the management priorities set by the panel of Delphi participants, there was little or no suitability in implementing reduced and no-till practices (scenarios 10 to 12) as a single measure to favor a more sustainable agro-production in the watershed. These scenarios reported the lowest CF (<0.014; Table A1) among the management alternatives and zero probability to be ranked in the first six positions across the four subcatchments (Fig. 2a and b). These results were explained by a reduction in the corn and soybean production in response to the transition to non-conventional tillage practices, which shortened the depth and efficiency of nutrient mixing through the soil profile affecting the plant nutrient uptake. Although the implementation of non-conventional tillage practices enhanced some of the watershed ecosystem services, it contravened agricultural production, the top priority for the KRW under this preference scheme, and therefore should be discarded unless combined with complementary measures.

3.2.1. *Upper and central subcatchments*

Regarding the remaining management alternatives, the C–C–S rotation scheme implemented in 25% and 50% (scenarios 06 and 07) of the plots currently under corn, soybean, or C–S rotation, were the most likely to be considered as the best alternatives for the upper and central subcatchments (Fig. 3a and c). It is important to highlight that these subcatchments have the highest percentage of area devoted to crop production in the KRW, estimated at 81.2% in the upper and 62.6% in the central. The RAI values in the 2040s for the upper subcatchment indicated that scenario 07 can be ranked in any of the first two positions with a cumulative probability of 40%, being 7% over scenario 06 and 20% or more over the remaining alternatives (Fig. 3e). For the same decade and ranks, the probabilities for scenarios 06 and 07 in the central subcatchment seemed to be tighter, with cumulative RAI values equal to 28% and 33%, respectively. According to the SMAA for the 2060s, these probabilities were expected to increase by 5% in both scenarios for the central subcatchment and an increase of 13% only in scenario 07 for the upper subcatchment (Fig. 3a). This means that these management alternatives may become even more relevant in these subcatchments in the long-term. Furthermore, the implementation of the C–C–S rotation was further validated by the CF, which ranged from 0.147 to 0.396.

3.2.2. *Middle and lower subcatchments*

In the middle and lower subcatchments, the RAI did not vary considerably from the 2040s to the 2060s. Specifically, in the middle subcatchment, scenarios 04 and 06 were slightly more likely to be ranked first or second (26%–29%; Fig. 3d) than the remaining alternatives (21%–25%; Fig. 3d). However, these differences were not significant as the CF was similar (0.097–0.165; Table A1) for all alternatives. This means that none of the management alternatives (i.e., scenarios 00 to 09) were sufficiently relevant for the given subcatchment and preference scheme, explaining why there were not temporal variations in the SMAA. In the lower subcatchment, a similar situation was observed except for scenarios 00 and 04, which stood out from the rest of the management alternatives. These scenarios reported a cumulative probability of being ranked in the top three positions of 42%–48% against 28%–38% observed for the remaining alternatives (Fig. 3d), being equivalent in the 2040s and 2060s. Although the CF was slightly larger for scenarios 00, 04, and 07 (0.144–0.174; Table A1), the CF was again not high enough compared to that for the rest of the alternatives

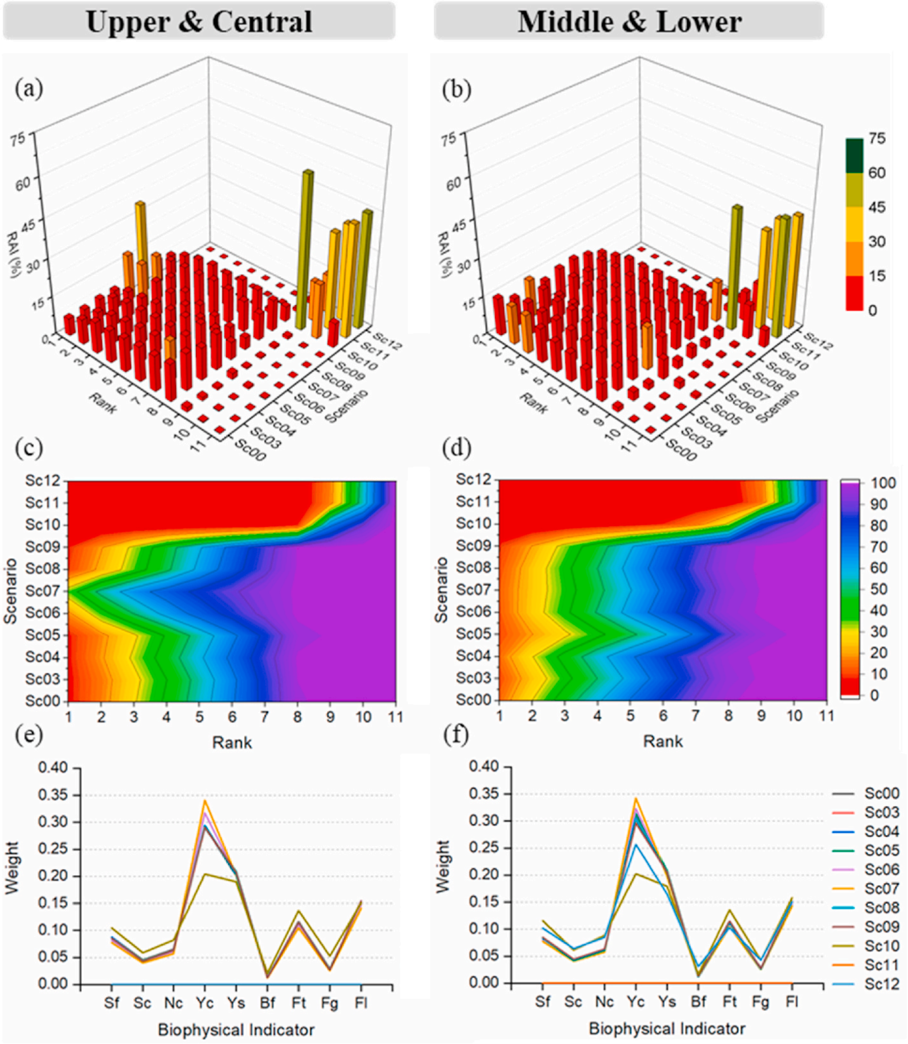


Fig. 3. Descriptive measures for the SMAA under the expert stakeholders' preference scheme. (a–b) RAI (%); (c–d) cumulative RAI (%); and (e–f) central weight vectors in the upper & central and middle & lower subcatchments, respectively.

(0.086–0.135; Table A1) to lean the decision towards the selection of any of them as the best management alternative.

3.2.3. Central weight vectors

Overall, the weigh vectors showed less complex tradeoffs when preference information was provided (Fig. 3e and f). According to the magnitude of the central weights, the indicators of crop production were the most varying (0.19–0.35) and can be considered the determinant criteria to identify the most suitable management alternatives. These parameters were followed by the number of flood events and the total fish species richness, which were used as surrogates for flood control and biodiversity. However, notice that the weight vectors for all the biophysical indicators besides corn and soybean yields, had similar magnitudes from one management alternative to the other (Fig. 3e and f), implying a similar systemic response.

Overall, the management alternatives that satisfied the optimization system were more easily identified for the most cultivated subcatchments (i.e., upper and central), while, for the less cultivated subcatchments, additional practices or information should be provided as none of the evaluated scenarios had a distinctive impact on the criteria spanning the ecosystem services. We believe this was due to the similar systemic response to the evaluated management alternatives, which being non-structural, had low capability to enhance the diverse set of ecosystem services. For example, the reduction of nitrogen rates, split application of nitrogen, and cover cropping can generate a reduction in nitrate loads of approximately 10–30% per acre (IEPA, 2015). However, if we compare this percentage to those expected with the implementation of wetlands and buffers, and the transition to perennial crops (up to 90%), these management practices are not prominent. Consequently, the formulation of management alternatives may be addressed at the subcatchment level using specific combinations of practices when needed to boost the enhancement of the ecosystem services present in each subcatchment.

3.3. Non-expert stakeholders’ preferences

3.3.1. Upper subcatchment

Using data collected during four focus groups with stakeholder in the KRW, the decision-making process seemed to be more conclusive for the upper subcatchment than for the rest of the watershed. The implementation of the C–C–S rotation scheme and cover cropping in 25%–50% of the plots under corn, soybean, or C–S rotation (scenarios 06 to 09) was equally likely (42%–44%) to be ranked as one of the top three management alternatives towards a more sustainable agro-production in the 2040s (Fig. 4a and c). These alternatives were closely followed by scenario 04 (40%-10%–50% N application in non-tiled C) with 38% and in a minor proportion by scenarios 00 (no action), 03 (50%–50% N application in tiled C), and 05 (C–S rotation in any C or S plot) with a difference in the cumulative RAI of more than 10% (Fig. 4c). The management alternatives associated with the implementation of non-

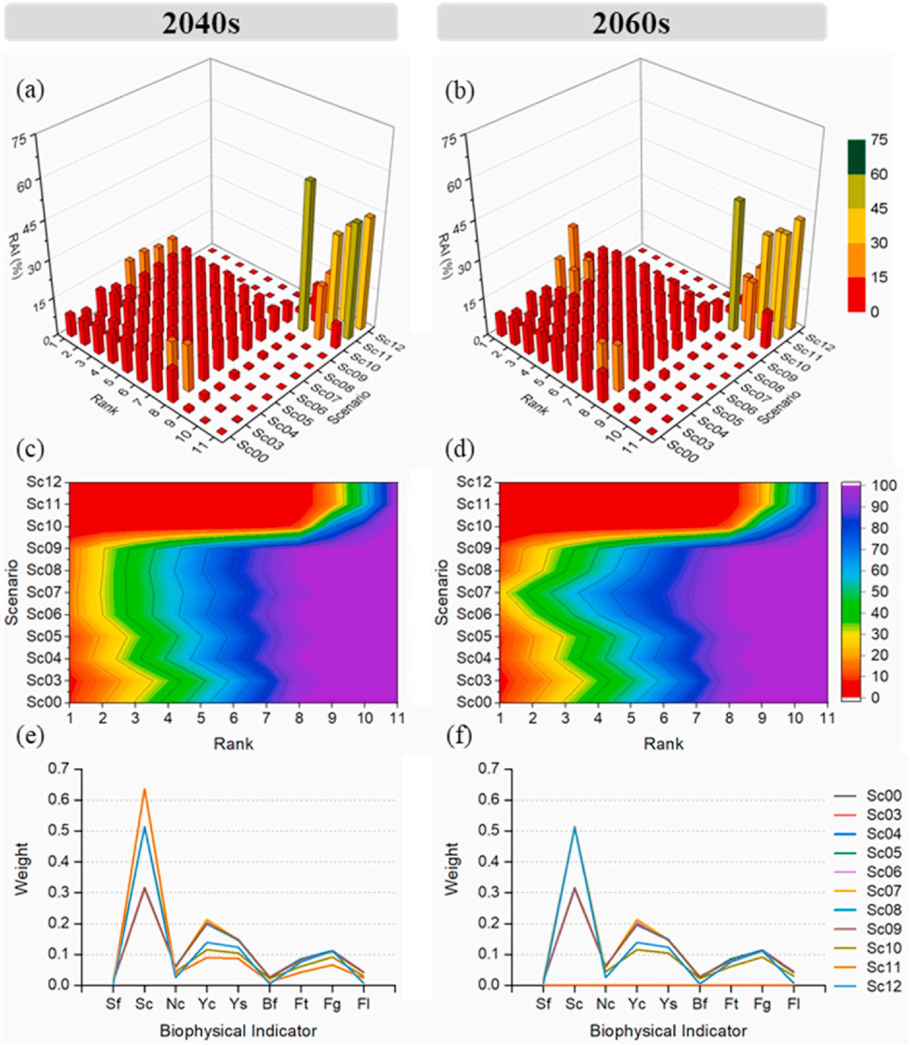


Fig. 4. Descriptive measures for the SMAA in the upper subcatchment under the preference scheme expressed by stakeholders from the general population. (a–b) RAI (%); (c–d) cumulative RAI (%); and (e–f) central weight vectors for the 2040s and 2060s, respectively.

conventional tillage practices (scenarios 10 to 12) were highly likely (38%–58%) to be ranked as the three least efficient alternatives as observed for the previous two preference schemes (Fig. 4a and c). By the 2060s, scenarios 06 and 07 (C–C–S rotation in any C, S, or C–S plot) improved their chances to be rank in the first two positions, showing the highest cumulative RAI (33%–43%; Fig. 4b and d). These results agreed with those observed under the expert and local leaders' preferences, but only for the 2060s. The constraints imposed by the sample of stakeholders from the general population only made evident the relevancy of scenarios 06 and 07 in the long-term as crop production was not the top priority for them.

3.3.2. Middle, central, and lower subcatchments

For the middle, central, and lower subcatchments, the decision-making process subjected to the non-expert stakeholder's preference was ambiguous. All management alternatives (including no action), besides scenarios 10 to 12, obtained the same probability (6%–16%) of being ranked in any of the first eight positions, and CF values ranged from 0.094 to 0.167 (no significant difference; Table A1) without important changes from the 2040s to the 2060s. This means that the level of importance expressed by non-expert stakeholders did not provide efficient alternatives and did not seem in line with the watershed needs. We believe this may be related to the information gap between the expert stakeholders and the non-expert stakeholders that was evidenced in the preference information expressed by these two stakeholder groups. Because no-action was equally likely as the remaining alternatives, except for non-conventional tillage, other management alternatives, including combination sets of the evaluated in this study, may be discussed with the stakeholders and evaluated anew for their implementation suitability.

3.3.3. Central weight vectors

Under this preference scheme, the central weight vectors for the upper subcatchment showed minimal or no relevance to streamflow (Sf), nitrogen concentration (Nc), forest biomass (Bf), or flood events (Fl) in the selection of the best management alternatives (Fig. 4e and f). Sediment concentration (Sc), on the other hand, was the most relevant criterion (0.30–0.65; Fig. 4e and f), followed by crop production (Yc, Ys; 0.8–0.21; Fig. 4e and f) and, in a minor proportion, by game-fish species (Fg; 0.05–0.10; Fig. 4e and f). These biophysical indicators are associated with the three main categories of ecosystem services present in the KRW (production, environmental soundness, and social relevancy; Table 2), and showed how, for non-expert stakeholders, the distinct ecosystem services were a priority. On the contrary, expert stakeholders prioritized production and environmental soundness over social relevancy (Table 1). However, it is not clear if the expert stakeholders' preferences obeyed technical aspects or the underestimation of the cultural/aesthetic ecosystem services and their relevancy for the wide spectrum of stakeholders of the KRW.

Despite the central weight vectors described the preference information shown in Table 3, differences in the systemic response to the management alternatives were predominantly between scenarios 10 to 12 and the remaining ones (Fig. 4e and f). This behavior was observed in the SMAA for all the subcatchments under the non-expert stakeholders' preferences, which, as suggested before, indicates that the overall response to scenarios 00 to 09 was similar and hence, the implementation of complementary practices groups should be address in future research.

4. Conclusions

This study developed a framework to evaluate the trades-off of implementing different land management practices aimed at enhancing 13 watershed ecosystem services under climate change projections. The study incorporated hydrologic-model projections of nine biophysical indicators and surrogates, 13 non-structural management alternatives, and three preference schemes into a unified SMAA to identify the most suitable alternatives for implementation according to stakeholder expectations. Results indicated that preference information on watershed ecosystem services is crucial to guide the decision-making process when a wide spectrum of criteria is considered to assess the systemic response to several management alternatives. However, differences in the preference information observed from two samples collected during a month-long Delphi study and series of four focus groups suggested that there may be information gaps within government institutions, decision makers, and local communities as well as real differences in preferences.

If the experts engaged as part of our Delphi process were given priority, the C–C–S rotation scheme (scenarios 06 and 07) is expected to offer the best management alternative to ensure a sustainable agro-production system in the most cultivated subcatchments of the KRW (i.e., upper and central). The SMAA indicated that this practice would satisfy the production goals without significantly affecting the remaining criteria. On the contrary, for the less cultivated subcatchments, none of the management alternatives (no action, split N application, crop rotation, cover cropping) signaled a distinctive systemic response. Consequently, the formulation of management alternatives may need to be addressed at the subcatchment level using specific sets that combine several management practices to integrally enhance the ecosystem services present in each subcatchment. Under the preferences expressed by the general population, the implementation of the C–C–S rotation scheme and cover cropping (scenarios 06 to 09) was equally likely (42%–44%) to be one of the best three management alternatives for the upper subcatchment in the 2040s. The C–C–S rotation became more relevant in the 2060s, two decades later than under the experts and local leader's preferences because crop production was not the top priority for the non-expert stakeholders. For the rest of the subcatchments, the level of importance expressed by the general population, despite being more diverse, did not provide efficient alternatives and did not seem to go in line with the watershed needs.

The disparity between preferences expressed by expert stakeholders engaged through a Delphi process and the general population of stakeholders (including experts and non-experts) showed different rankings of alternatives across several subcatchments. These findings suggest the level of level of expertise held by an evaluator manifests different observations and concerns about landscape change (Primdahl et al., 2018). Differences also could have been attributable to the different methodologies adopted to facilitate the research process. Both methodologies were participatory and inductive, therefore emphasizing the value of this research approach for understanding diverse stakeholder interests. Indeed, participatory research and deliberation is needed for balancing expectations and facilitating conversations between government institutions and local communities (multi-stakeholder consensus) (Kenter et al., 2011). Collaboration across stakeholder groups will help to identify management alternatives that are most desired by individuals who believe they may be affected by policy change (Shipley et al., 2020). Therefore, the framework employed in this study may serve as a starting point to establish a decision support system that identifies the most suitable management practices for implementation and simultaneously balances production goals, environmental soundness, and social relevancy. This will enable stakeholders to formulate timely adaptation and mitigating strategies to adapt to natural and anthropogenic changes.

Credit author statement

Juan S. Acero Triana: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Visualization. Maria L. Chu: Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Supervision, Funding acquisition. Nathan J. Shipley: Conceptualization, Writing – review & editing. Carena J. van Riper: Conceptualization, Writing – review & editing, Supervision. William P. Stewart: Conceptualization, Writing – review & editing, Supervision. Cory D. Suski: Conceptualization, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

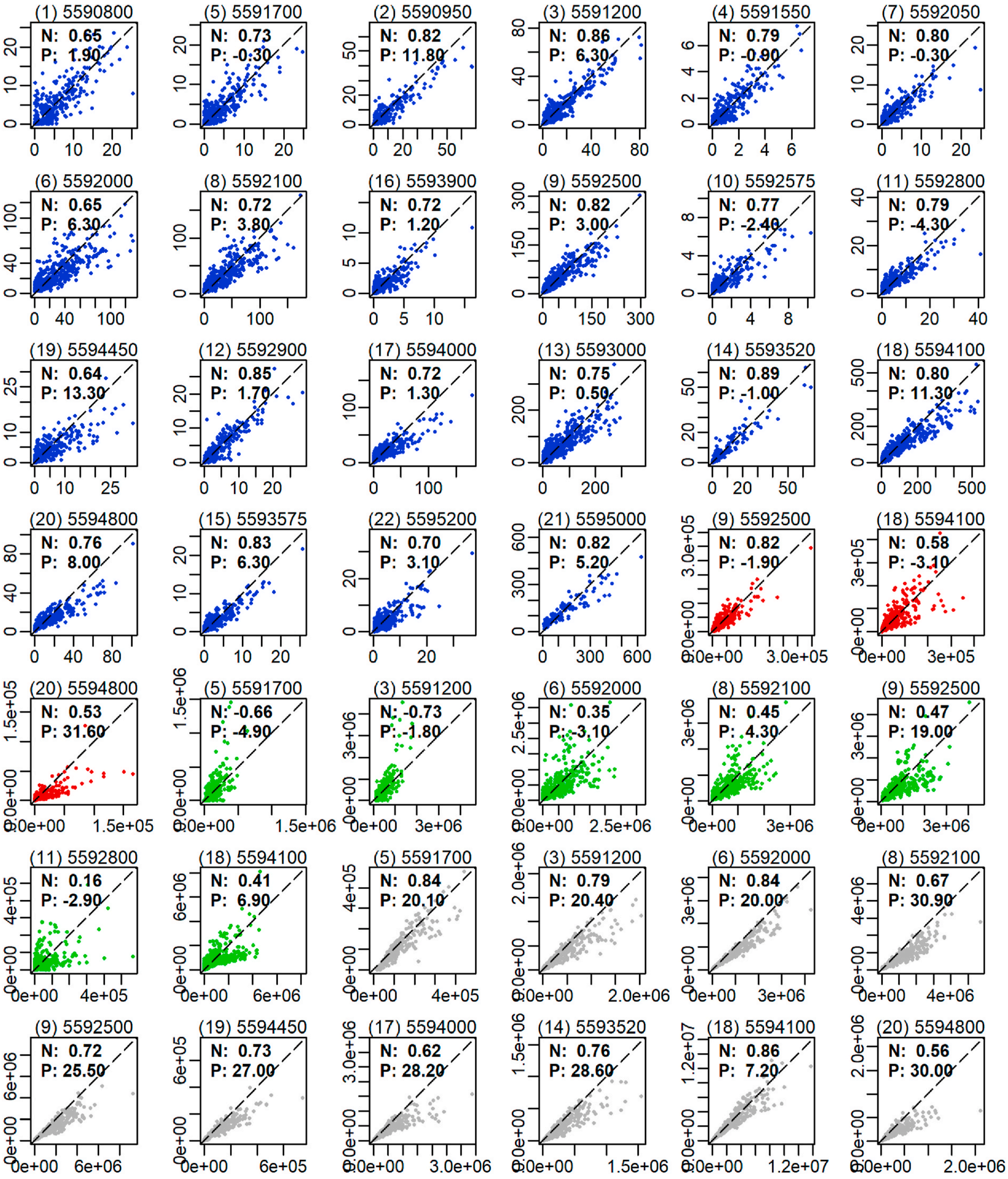

Fig. A.1. Scatterplots of observed (x axis) and simulated (y axis) values of streamflow (blue dots) and sediment (red dots), nitrate (green dots), and oxygen (grey dots) loads over the 1980–2017 period at monthly time step. The numbers in parenthesis are the Figure-1c labels and the 7-digit numbers the USGS gauge codes, and N and P the NSE and PBIAS values, respectively.

Table A.1
CF for each management alternative under the three evaluated preference schemes

	Decade	Sc00	Sc03	Sc04	Sc05	Sc06	Sc07	Sc08	Sc09	Sc10	Sc11	Sc12
Upper	*No preference*											
	2040s	0.108	0.099	0.132	0.122	0.147	0.158	0.138	0.140	0.054	0.031	0.038
	2060s	0.110	0.096	0.122	0.119	0.149	0.219	0.131	0.128	0.049	0.031	0.036
	Expert stakeholders											
	2040s	0.080	0.081	0.102	0.092	0.196	0.276	0.112	0.108	0.001	N/A	N/A
	2060s	0.074	0.072	0.083	0.080	0.198	0.396	0.093	0.085	0.000	N/A	N/A
	Non-expert stakeholders											
	2040s	0.088	0.063	0.114	0.101	0.172	0.169	0.159	0.151	0.003	0.003	0.000
	2060s	0.086	0.059	0.093	0.091	0.184	0.279	0.124	0.112	0.002	N/A	0.000
Middle	*No preference*											
	2040s	0.125	0.115	0.152	0.120	0.117	0.093	0.132	0.133	0.080	0.035	0.040
	2060s	0.132	0.119	0.146	0.123	0.126	0.114	0.132	0.127	0.078	0.030	0.039
	Expert stakeholders											
	2040s	0.116	0.110	0.143	0.162	0.147	0.118	0.117	0.107	0.014	N/A	N/A
	2060s	0.113	0.111	0.134	0.165	0.160	0.141	0.113	0.097	0.011	N/A	N/A
	Non-expert stakeholders											
	2040s	0.108	0.106	0.129	0.124	0.118	0.094	0.123	0.113	0.060	0.023	0.027
	2060s	0.120	0.105	0.124	0.127	0.117	0.097	0.123	0.112	0.053	0.023	0.027
Central	*No preference*											
	2040s	0.156	0.098	0.118	0.141	0.120	0.129	0.126	0.135	0.053	0.034	0.036
	2060s	0.181	0.098	0.122	0.146	0.124	0.149	0.114	0.115	0.052	0.033	0.034
	Expert stakeholders											
	2040s	0.102	0.095	0.105	0.170	0.147	0.203	0.109	0.093	0.003	N/A	N/A
	2060s	0.113	0.087	0.099	0.177	0.154	0.245	0.091	0.079	0.002	N/A	N/A
	Non-expert stakeholders											
	2040s	0.115	0.099	0.114	0.112	0.121	0.128	0.133	0.146	0.029	0.015	0.019
	2060s	0.131	0.103	0.117	0.121	0.123	0.133	0.118	0.117	0.031	0.017	0.019
Lower	*No preference*											
	2040s	0.235	0.107	0.150	0.099	0.107	0.099	0.122	0.119	0.056	0.028	0.028
	2060s	0.262	0.105	0.153	0.100	0.110	0.115	0.116	0.111	0.059	0.025	0.028
	Expert stakeholders											
	2040s	0.153	0.121	0.152	0.115	0.131	0.144	0.118	0.094	0.003	N/A	0.000
	2060s	0.174	0.115	0.147	0.116	0.135	0.173	0.105	0.086	0.002	N/A	0.000
	Non-expert stakeholders											
	2040s	0.158	0.116	0.137	0.109	0.131	0.123	0.119	0.104	0.011	0.004	0.002
	2060s	0.167	0.111	0.136	0.107	0.131	0.128	0.115	0.105	0.013	0.007	0.002

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