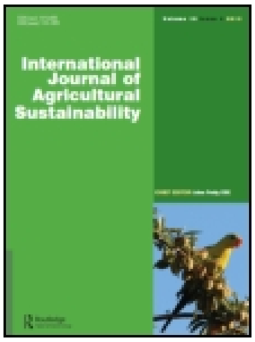

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A farm-scale biodiversity and ecosystem services assessment tool: the healthy farm index

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Farm management focused on maximizing biomass production results in biological simplification and ultimately a degraded production potential for the future. Despite the large and growing body of evidence pointing to the need to restore biodiversity to farm systems, incorporation of biodiversity and ecosystem services into local agricultural land-use decision-making remains limited. The lack of planned and associated biodiversity may reduce resiliency of local managed ecosystems and add management costs; however, the tradeoff for individual landowners of greater diversity is increased management complexity and uncertainty. To assist farmers in managing biodiversity and to encourage ecological thinking, we developed the Healthy Farm Index, a farm-scale tool that complements existing farm assessment tools by integrating multiple metrics and outputs suitable for applied decision-making and annual evaluation. In this article, we describe the impetus for the index development and the structure of the index and through a case study apply the index and discuss its varied outputs and applications.

Keywords: adaptive management; agroecology; engagement; organic

Introduction

Diversity and complexity are fundamental to healthy systems, whether health is measured by economic, ecological or social indicators (Tilman 1999). Biological diversity supports healthy ecological systems (Benton *et al*. 2003, Perrings *et al*. 2006). In particular, a diversity of genes, species and ecosystems are essential to the continued flow of ecosystem services (MA 2005, Perrings *et al*. 2006, Dale and Polasky 2007). In agroecosystems, ecosystem services provided at these respective biological levels include genes for drought tolerance, species that pollinate and control pests and land cover that regulates water flow (Swinton *et al*. 2007, Zhang *et al*. 2007) as well as the primary ecosystem service of a farm, biomass production. Yet, the recent intensity of management and singular focus on maximizing crop and livestock production has unintentionally resulted in the decline of biodiversity and ultimately the reduction of other ecosystem services provided by agroecosystems (Matson *et al*. 1997, Altieri 1999, MA 2005, Norris 2008, Bennett *et al*. 2009). Restoration of biological diversity in agricultural ecosystems may provide an improved flow of ecosystem services to the farm as well as the larger landscape (Daily 1997, Boody *et al*. 2005, Zhang *et al*. 2007, Chaplin-Kramer *et al*. 2011) and aid species conservation efforts (Beecher *et al*. 2002).

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Despite the large and growing body of evidence pointing to the need to restore biodiversity to farm systems (Jackson *et al*. 2007, Rands *et al*. 2010, FAO 2011), incorporation of biodiversity and ecosystem services into agricultural land-use decision-making remains limited. Moreover, opportunity costs accumulate as biodiversity is ignored and lost (Perrings *et al*. 2006). Limited adoption may stem from market structures, lack of incentives (Lin 2011, Reganold *et al*. 2011), limited awareness of the need for nature conservation in agroecosystems or what this entails (Ahnström *et al*. 2009), lack of awareness of potential benefits, perception that biodiversity has a negative impact on farm profitability (Conover 1998) or the uncertainty and complexity in perceived outcomes (Hammond *et al*. 1998, Ahnström *et al*. 2009, Bennett *et al*. 2009).

To encourage and support a more comprehensive on-farm decision-making process that integrates biological diversity and ecosystem services, we have developed and tested a multi-metric and descriptive farm assessment tool, the Healthy Farm Index (HFI). To date, the focus of farm assessment tools has largely been agricultural resource conservation, specifically, the abiotic resources, such as water, soil and nutrients, necessary for continued biomass production (e.g. Zobeck *et al*. 2008). When included, biodiversity and associated ecosystem services are ancillary metrics. However, this approach minimizes the importance of biodiversity. Thus, to incorporate biodiversity and ecosystem services more intimately into farm decision-making, we employ a needed agricultural–environment management approach (Kevan *et al*. 1997, Weiner 2003, Batie 2009), while incorporating concepts from multiple disciplines, including agronomy, economics and human dimensions. Furthermore, measurement of biodiversity and ecosystem services places the HFI under the framework of the Millennium Ecosystem Assessment (MA 2005) rather than trying to find a place within the varied applications and definitions of sustainability (Pollock *et al*. 2008).

In this article, we first outline the index structure, discussing the selection of suitable metrics, targets and weights. Second, we describe a case study of the initial field application of the HFI to a network of organic farms that collaborated in the index development and data collection effort. Third, with calculated metrics from the participating farms, we evaluate and discuss the response of the index to metric targets and weights. In conclusion, we suggest future development and application of the HFI as an assessment tool for adaptive management.

Materials and methods

The HFI uses multiple metrics to form a composite indicator or multimetric index (Karr and Chu 1997, Girardin *et al*. 1999, Saltelli *et al*. 2008) built on an interrelated hierarchy of biodiversity composition and associated ecosystem services (Bennett *et al*. 2009, Dennis *et al*. 2010, Mace *et al*. 2011). Proposed and tested as a conceptual model on hypothetical farm scenarios (Quinn *et al*. 2009), the selected metrics focus on the relationships among farm management, biodiversity maintenance and the flow of ecosystem services. The metrics provide a general framework that can be adapted for monitoring associated outcomes of farm management across farm types and global ecoregions. Chosen metrics reflect current information available to farmers or new data collected easily by farmers at the farm scale. As a composite indicator, the HFI avoids the limitations of focusing on a single outcome or measure of success (Kosoy and Corbera 2010) and reflects the variety of key attributes of an agroecosystem, emphasizing integrated agricultural–environment management rather than the less-encompassing agriculture resource conservation (Batie 2009). The HFI, however, does not seek to replace other measures of agricultural resource conservation (e.g. soil quality; Zobeck *et al*. 2008), but rather to compliment current tools available.

Scale of application

There is a clear need to integrate biodiversity and ecosystem services into the management of agroecosystems (Perrings *et al*. 2006, Pretty *et al*. 2010, Quinn 2012). Furthermore, given evidence supporting the need to include local stakeholders (Dawson *et al*. 2008, Persha *et al*. 2011, Fischer *et al*. 2012), it is clear that farmers must be involved in the process of local management for biodiversity and ecosystem services, that tools need to be suitable for farmer use (Lightfoot and Noble 2001, Darnhofer *et al*. 2010, Cerf *et al*. 2012), and that management must consider suitable scales (Darnhofer *et al*. 2010). Thus, we designed the HFI as a farm-scale assessment tool that aids individual landowners in monitoring and managing biodiversity and ecosystem services within a single farm system. Other projects have assessed environmental health or biodiversity and ecosystem services at watershed, regional or global scale (e.g. Piorr 2003, Chan *et al*. 2006, Esty *et al*. 2006, USDA CEAP, Nelson *et al*. 2009, Floridi *et al*. 2011). Although these larger-scale measurements are of value to governments and policy makers, they are not effective tools for individual landowners because of the broad spatial and temporal scales over which they measure.

Index structure: biodiversity and ecosystem services

Structured to integrate existing knowledge regarding biodiversity and ecosystem service metrics, metrics in the index are categorized as either a marker of the current status of biological diversity composition or indicator of the flow of an ecosystem service. Within these two categories, the HFI includes metrics (Table 1) that are relevant to biodiversity in agroecosystems at the farm scale and predicted to affect the flow of ecosystem services to the farm and surrounding landscape. The composition of biodiversity on a farm is an indicator of ecosystem health, whereas flow of ecosystem services encompasses the benefits or ecosystem services provided to the farm and surrounding environment (de Groot *et al*. 2002, Tscharntke *et al*. 2005, FAO 2007). At this time, the HFI considers the composition of biodiversity across two levels of biological organization: species and ecosystems. The assessment of ecosystem services includes provisioning, regulating

Table 1. From left to right; Index categories of biodiversity (species and ecosystem diversity) and ecosystem service (provisioning, regulating and cultural), selected metrics in the HFI and data source.

Category	Metric	Source of case study data		
Species diversity	Planned vegetation richness	Farm questionnaire	Biodiversity score	Healthy farm Index
	Livestock richness	Farm questionnaire		
	Avian indicator species	Researcher and farmer observation		
	Native/total ratio	Researcher and farmer observation		
Ecosystem diversity	Richness of landscape elements	Farm maps/farm questionnaire		
	Percent non-crop	Farm maps/farm questionnaire		
	Percent rare landscape elements	Farm questionnaire		
Provisioning services	Yield average	Farm questionnaire	Ecosystem service score	
	Market opportunities	Farm questionnaire		
Regulating services	Percent of waterways buffered/sheltered	Farm maps		
	Percent of farm fields protected	Farm maps		
	Percent continuous living cover	Farm questionnaire		
Cultural services	Satisfaction	Farm questionnaire		
	Tenure	Farm questionnaire		

and cultural services (Zhang *et al*. 2007). Data needed for the assessment process are immediately available to farmers (e.g. yield, cropping patterns, satisfaction), easy to sample with little training (bird metrics) or readily available from open data sources (e.g. Google Earth land cover images). Moreover, the metrics are not region specific, thus allowing the concept of the HFI to be adapted to and applied across agroecosystem types.

Metrics of biodiversity composition

Metrics of biodiversity include measures of planned as well as associated species and ecosystem diversity (Matson *et al*. 1997). As a complete biodiversity inventory is not practical (Büchs 2003, Dale and Polasky 2007), the HFI uses accurate and suitable indicator species or groups. As species-level metrics of planned diversity (i.e. diversity deliberately maintained on a farm and includes crops, livestock or landscape elements), the HFI includes the richness of field plantings (i.e. cash crops and cover crops) (Lin 2011) and livestock types. Associated biodiversity encompasses species and ecosystems that interact with a farm system but are not typically managed as part of a farm operation. As a species-level metric of associated diversity, the HFI focus on wild bird diversity, in particular a small set of identified suitable indicator species (Quinn *et al*. 2011) of regional conservation interest (e.g. Rich *et al*. 2004). Birds stand as an ideal indicator species and are preferable to insects or plants because of their ease of detection, sensitivity to environmental change and broad presence in the environment (Browder *et al*. 2002). In addition, targeting a limited number of relevant indicator species is more suitable to farmer engagement than metrics like species richness. An additional associated bird diversity measure is a native-to-total species ratio (National Academy of Sciences 2000). HFI ecosystem-level metrics include the abundance of rare landscape elements (e.g. wetlands, riparian areas, primary forest and prairie), percent of the farm in non-crop vegetation and richness of land cover types.

Metrics of ecosystem services

Metrics of ecosystem services include measures of provisioning, regulating and cultural services. Current predictability of the flow of ecosystem services is more limited than measures of species and ecosystem diversity (Kremen 2005, Bennett *et al*. 2009, Rands *et al*. 2010). For example, although an increase in insectivores may result in greater consumption of pest insects, directly linking this predation to a reduction in crop damage is difficult (Letourneau and Bothwell 2008). We recognize that functional outcomes of many practices are uncertain and predictions are often limited to extrapolating from the scope of practices implemented in the landscape (Bennett *et al*. 2009). With acknowledgement of this uncertainty, the HFI, by using current research and reviewing relevant literature to estimate trends in ecosystem services resulting from shifts in biodiversity patterns, can be used to emphasize outcomes of farm management. For example, planting of buffer strips is widely recognized to decrease runoff from crop fields, yet the quantified value of total soil loss or chemical capture is contingent on a wide variety of other field and landscape factors (Dosskey *et al*. 2008). These points do not diminish the value of the HFI but rather reflect the status of ongoing research to clarify relationships between farm practices and ecosystem service outcomes and the need to act on existing knowledge (Fischer *et al*. 2012).

The primary ecosystem service provided by agroecosystems is provisioning of biomass. As metrics of provisioning services, the HFI measures yields of selected common regional crops (e.g. corn, soybean and wheat in the central United States) and alternate income opportunities provided by biodiversity or nature (e.g. ecotourism or specialty products). As metrics of regulating services, the HFI measures conservation structures such as field buffers and use of continuous living cover to indicate soil retention (Borin *et al*. 2010). To assess water regulation, the HFI measures the percent of waterways protected by buffers (Dosskey *et al*. 2008, Udawatta *et al*. 2011). Cultural services are measured by land tenure (Soule *et al*. 2000), calculated as the percentage of farmed land owned by the farmer, and a self-evaluation of individual satisfaction with farm profit and the farm management system. We selected satisfaction with profit over gross or net profit to reflect an individual's perception of success as the goals of an individual farmer can vary.

Selection of metric targets and index weights

To make the HFI broadly applicable, selection of targets is deliberately flexible to be context specific for unique location of a farm, available resources and labour and objectives of the individual (Karr and Chu 1997, Dale and Haeuber 2001, Darnhofer *et al*. 2010). Selection of metric targets and weights though must take into account the ecoregion a farm is within, available science and objectives of the landowner; and reflect the current biodiversity crisis (Norris 2008) and the need to put into practice management actions that support ecosystem services (Daily and Matson 2008). The identification of metric targets and weights is a collaborative process between local researchers, practitioners and farmers, though farmer input is essential throughout the process to ensure that the identified goals are applicable and realistic.

Metric targets

Metric targets represent a goal as identified by the collaborative process involving local farmers and researchers. Although biodiversity conservation is implicit in the use of the HFI, importantly, the goal of the index is not to encourage farmers to maximize biodiversity but rather to restore and maintain a level of diversity beneficial to the farm and local ecosystem and that contributes to local and regional conservation efforts. Furthermore, observation of natural systems and replicated field trials demonstrate that increasing richness and diversity improves the flow of many ecosystem services (e.g. Tilman *et al*. 2006). The benefits, however, of increasing biodiversity do not increase indefinitely; the value provided is subject to the law of diminishing returns and spatial and temporal variation (Kremen and Ostfeld 2005, Tilman *et al*. 2006, Zhang *et al*. 2012). Thus, rather than establishing an idealistic (and ultimately impractical) objective to maximize all metrics, the HFI allows farmers to focus on pragmatic goals for each metric, to select suitable targets and over time, to examine emerging trade-offs and synergies.

Identification of region- and farm-specific targets for each metric is accomplished in two ways: (1) calculated with numerical determinants (e.g. average or maximum) or (2) based on empirical research. Average and maximum targets represent mean and highest observed per metric, respectively, on farms scored within a selected region. Empirical targets would reflect published literature, local research, discussion with local farmers and informal observations in the field. Engagement of the local research community in selection of these targets would prove valuable. Ultimately, targets should be ecoregion specific and take into consideration individual farm goals.

The metric values obtained from the farm are standardized against the chosen target (i.e. Observed Metric Value/Target Metric Value), resulting in metric scores between zero and one, with higher values reflecting better performance (Box 1). When an observed measure of a metric exceeds the selected target for that metric, the index adjusts the scored value to one, limiting the ability of a single metric to compensate for shortcomings elsewhere and the potential of a single metric to overwhelm other measures.

Box 1 Calculation of composite scores in the Healthy Farm Index.

Step 1. Standardize metrics between 0 and 1
- Farm result/target = Standardized metric score

Step 2. Adjust by selected weight 1 (category)
- Standardized metric score * Sub-category weight = Sub-weighted score

Step 3. Sum sub-weighted scores in category, adjust by selected weight 2
- Σ (Weighted scores in category) * Category weight = Category index score

Step 4. Sum index scores
- Σ (Biodiversity index scores) = Biodiversity index
- Σ (Ecosystem service index scores) = Ecosystem service index

Step 5. Average of biodiversity and ecosystem service index
- (Biodiversity index + Ecosystem service index)/2 = Healthy farm index

Category weights

Users of the HFI identify weights for each metric and each metric category (Table 2). To optimize HFI effectiveness, weights for each metric should reflect management goals for a region and priorities of the landowner. For example, if water quality were of particular interest to an individual farmer or to regional management efforts, greater weight can be given to metrics of regulating ecosystem services. Other example metric weightings could be made based on goals for crop production or nature conservation. Adjusting weights empower the landowner in the decision-making and assessment process and yet the format of the HFI ensures that multiple measures are included in the farm assessment process. It is important, however, to remember that the primary focus of the HFI is not which farm is better but rather to illustrate to the farmer a farm's success at conserving, maintaining and benefiting from biodiversity conservation and ecosystem services.

Application of the HFI is currently available as a digital spreadsheet. In the spreadsheet, farmers enter the scores for their individual farm and the selected targets and weights. An overall HFI score and a standardized score for each individual metric is available for evaluation.

Great Plains organic case study

To demonstrate the assessment process and subsequent output of the index, we present a case study as an initial application of the index. This case study focused on a group of 23 organic farms in the Great Plains region of North America (Figure 1). In this case study, we considered empirical, average and maximum targets. We evaluated metric and category weights (Table 2) for one neutral or non-specific monitoring plan with weights distributed equally across metric categories and for two specific management goals: grassland bird conservation or crop production. For grassland bird conservation (Table 2, Conservation column), the outcome of management on the state of grassland birds, a regional conservation priority (Rich *et al*. 2004), was given the greatest weight. For crop production, metrics of crop diversity and yield were given the greatest weight (Table 2, Production column).

For this case study, we worked with a local organic farming community. Although the total acreage of land managed under organic practices is relatively small (e.g. 58,679 ha on > 200 farms in Nebraska, USA of arable cropland, pasture and range), it is increasing across the Great Plains (USDA 2009). Twenty-three organic farmers, from two adjacent agroecoregions in the Great Plains (Figure 1), participated. Land use and land cover of the Great Plains region

Table 2. Selected category and metric weights for three different management goal examples applied for the Great Plains Organic case study: Equal, grassland bird conservation and crop production.

		Selected Weights Conservation							
		Equal		Conservation		Production			
Category	Metric	Category	Metric	Category	Metric	Category	Metric		
Species diversity	Planned vegetation richness	0.25	0.50	0.25	0.50	0.50	0.50	Biodiversity score	Healthy farm Index
	Livestock richness		0.50		0.50		0.50		
	Grass indicator species	0.25	0.33	0.50	0.50	0.25	0.33		
	Shrub indicator species		0.33		0.25		0.33		
	Native/total ratio		0.33		0.25		0.33		
Ecosystem diversity	Richness of landscape elements	0.50	0.34	0.25	0.34	0.25	0.34		
	Percent non-crop		0.33		0.33		0.33		
	Percent rare landscape elements		0.33		0.33		0.33		
Provisioning services	Yield average	0.34	0.50	0.34	0.90	0.50	0.90	Ecosystem service score	
	Market opportunities		0.50		0.10		0.10		
Regulating services	Percent of waterways buffered/sheltered	0.33	0.34	0.33	0.34	0.25	0.34		
	Percent of farm fields protected		0.33		0.33		0.33		
	Percent continuous living cover		0.33		0.33		0.33		
Cultural services	Satisfaction	0.33	0.50	0.33	0.50	0.25	0.50		
	Tenure		0.50		0.50		0.50		

Figure 1. Study regions and farm locations in the Great Plains of North America. Points represent participating farms.

Table 3. Summary data applied for the Great Plains Organic case study from two regions: Central Great Plains (CGP) and Western Corn Belt (WCB).

Metric	Region	Mean*	SD	Min.	Max.*	Empirical target*
Planned vegetation richness	CGP	4.17	1.47	3.00	6.00	7.00
	WCB	3.90	1.73	1.00	7.00	
Livestock richness	CGP	1.33	1.21	0.00	3.00	3.00
	WCB	2.70	1.77	0.00	5.00	
Grass indicator sp. score (0–1)	CGP	0.39	0.46	0.00	1.00	1.00
	WCB	0.48	0.28	0.00	0.94	
Shrub indicator sp. score (0–1)	CGP	0.78	0.15	0.50	0.94	1.00
	WCB	0.84	0.16	0.50	1.00	
Native/total ratio	CGP	0.93	0.03	0.89	0.98	1.00
	WCB	0.94	0.02	0.90	0.96	
Richness of landscape elements	CGP	4.50	1.76	3.00	7.00	8.00
	WCB	4.10	2.18	1.00	8.00	
Percent non-crop	CGP	0.22	0.16	6.25	49.07	0.15
	WCB	0.38	0.28	0.99	86.84	
Percent rare landscape elements	CGP	0.06	0.06	1.79	16.36	0.10
	WCB	0.11	0.12	0.00	31.37	
Yield average	CGP	101.91	21.49	74.44	133.33	100.00
	WCB	61.44	26.72	0.00	96.67	
Capture of market opportunities (Y/N)	CGP	50% (3/6) farms captured market opportunity				1.00
	WCB	50% (5/10) farms captured market opportunity				
Percent of waterways buffered/sheltered	CGP	85.00	30.00	40.00	100.00	100.00
	WCB	95.00	7.64	80.00	100.00	
Percent continuous living cover	CGP	66.67	51.64	0.00	100.00	100.00
	WCB	80.00	42.16	0.00	100.00	
Percent of farm fields protected	CGP	55.0	32.7	10.00	100.00	100.00
	WCB	76.0	28.4	30.00	100.00	
Satisfaction (1–6)	CGP	4.71	0.67	4.08	5.92	6.00
	WCB	4.90	0.43	4.14	5.71	
Land tenure (percent land-ownership)	CGP	0.91	0.14	71.35	100.00	100.00
	WCB	0.76	0.26	35.49	100.00	

Note: *Targets used in case study.

have undergone dramatic change from their historical grassland cover. Today, the study area is primarily agricultural, in particular, conventional and genetically modified corn and soybean (Henebry *et al*. 2005, Ellis and Ramankutty 2008). The applied targets (derived from Table 3) and weights (Table 2) are specific to the WCB and Central Great Plains temperate agroecoregions.

The organic farmers managing the farms were ideal to work alongside because their farm systems already included greater biodiversity than many conventional systems (Beecher *et al*. 2002, Hole *et al*. 2005). As such, they are already dealing with many components of biodiversity and, consequently, are involved in a more complex decision-making process than are conventional farmers.

We collected the applied data of farm biodiversity and ecosystem services for this case study (Table 3) between 2007 and 2009 with farmer questionnaires, on-farm discussion, field research and field maps from the farmers and governmental agencies (Table 1). We sampled avian communities during the summer breeding seasons of 2007–2009 as part of an associated project (Quinn *et al*. 2012). Land use and land cover data were provided by individual farmers, USDA, and USFWS and verified during farm visits. In the winter of 2008/2009, a mail survey

Table 4. Variation in HFI, biodiversity and ecosystem service scores for three different target-type examples from two regions.

Region	Target type (equal weight)	HFI			Biodiversity composition			Ecosystem service		
		Median	Max	Min	Median	Max	Min	Median	Max	Min
Western Corn Belt	Average	0.85	0.95	0.63	0.86	0.96	0.47	0.81	1.00	0.69
	Max	0.64	0.79	0.44	0.55	0.79	0.30	0.76	0.89	0.42
	Empirical	0.69	0.87	0.52	0.75	0.90	0.33	0.74	0.88	0.41
Central Great Plains	Average	0.79	0.92	0.61	0.78	0.97	0.48	0.80	0.99	0.74
	Max	0.63	0.82	0.50	0.55	0.85	0.34	0.72	0.80	0.52
	Empirical	0.67	0.82	0.53	0.60	0.82	0.37	0.73	0.82	0.53

Table 5. Variation in HFI, biodiversity and ecosystem service scores for three examples of selected weights.

Region	Weight type (Avg. target)	HFI			Biodiversity composition			Ecosystem service		
		Median	Max	Min	Median	Max	Min	Median	Max	Min
Western Corn Belt	Equal	0.85	0.95	0.63	0.86	0.96	0.47	0.81	1.00	0.69
	Grassland bird	0.89	0.96	0.71	0.85	0.94	0.64	0.91	1.00	0.69
	Agronomic	0.88	0.94	0.72	0.85	0.94	0.66	0.92	1.00	0.55
Central Great Plains	Equal	0.79	0.92	0.61	0.78	0.97	0.48	0.80	0.99	0.74
	Grassland bird	0.82	0.91	0.66	0.74	0.97	0.45	0.88	0.99	0.79
	Agronomic	0.87	0.90	0.67	0.80	0.93	0.46	0.88	0.99	0.78

was sent to the broader organic farming community of Nebraska, including participants of this project, to assess measures of farm production and farmer attitude. Participating farmers provided yield data for three primary crops in the region: corn, soybean and wheat. University researchers initially analysed collected data. We provided initial results to participating farmers and followed by in-person discussions to examine the different metrics during off-season advisory meetings.

Results

Of the 23 initial participants, 10 farmers in the WCB and 6 in the Central Great Plains provided sufficient information for complete assessment using the HFI. Individual farm HFI metric scores and subsequent index values were responsive to the selection of initial metric target values (Table 4). Weight selection had less of an impact on calculated HFI scores than did target selection (Table 5). Part of the reason for this may be that weights reflect the importance of different outcomes and, as such, only influence the aggregated sub-scores for the Biodiversity and Ecosystem Service components, which are then averaged to obtain the HFI. The variation in the composite scores does reflect the varied management choices made by individual farmers.

Examination of the overall HFI score and its two sub-scores is valuable for preliminary discussion on assessment output, but information is lost if one only considers a single number that masks the variability, uncertainty and the complexity of biodiversity and ecosystem services within agroecosystems. In addition, consideration of only one output likely limits future discussion. Therefore, following reflection on composite scores, discussion on individual metric scores provides greater information and value than consideration of only a single composite index value.

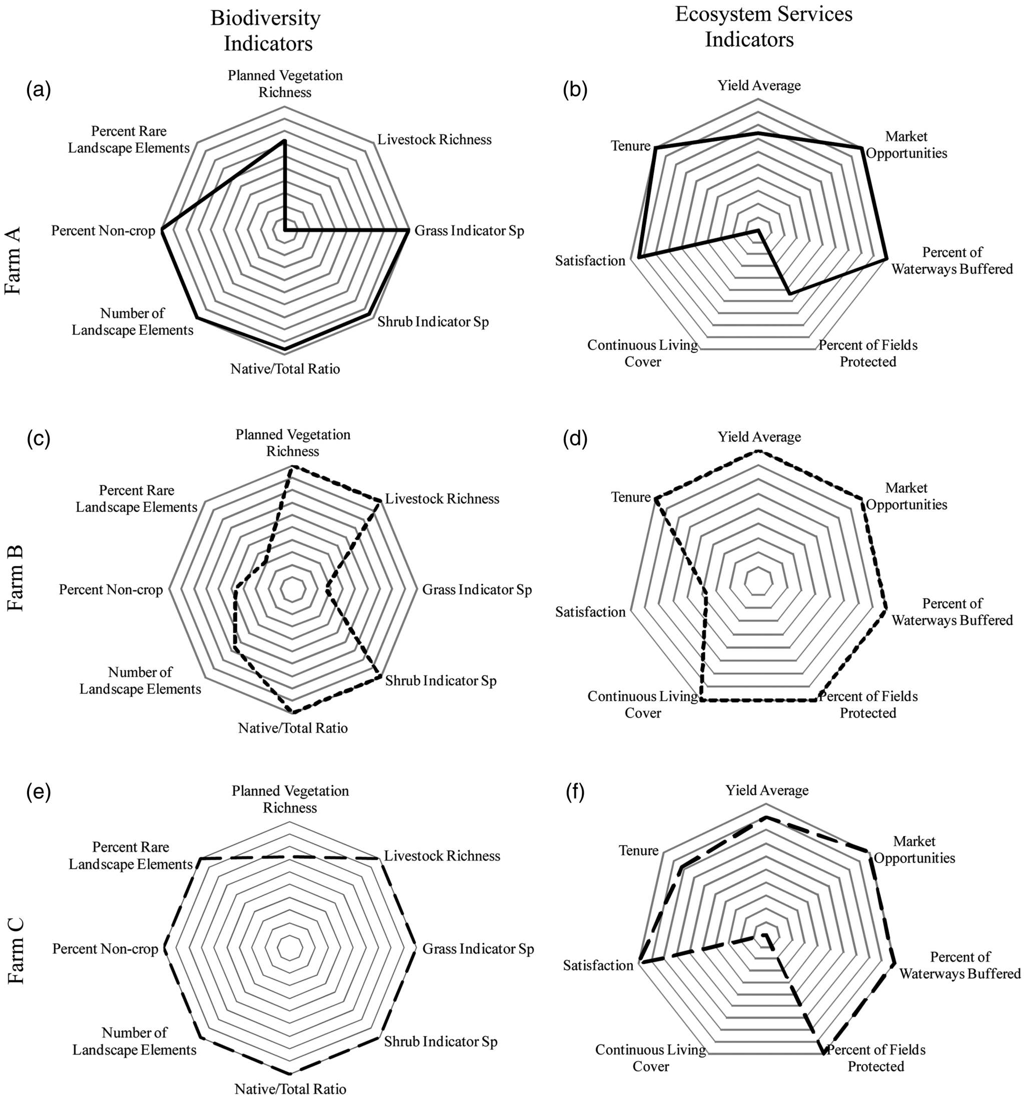

Figure 2. Variation observed on three farms for individual biodiversity and ecosystem service metrics. Note: Variation in measured values for three participating farms (rows) for individual biodiversity and ecosystem service metrics (columns). In the left column, the relative strengths and capacity to improve for each farm in regards to biodiversity is presented. Values closer to the perimeter represent measured values closer to the metric target. Taken together, a larger area within a star plots suggests greater progress towards stated goals. In the right column, strengths and areas to improve are presented for each ecosystem services metric. Plots are suited to identify relative strengths in a single assessment but are also valuable to compare among years or farms.

In this case study, variation among farms in individual metric scores in the Biodiversity and Ecosystem Service Categories was evident (Figure 2), providing information to the landowner regarding how well a farm is performing in relation to specific goals.

Examination of individual metrics can aid the landowner in setting pragmatic goals for improving each indictor. Spider plots (Figure 2) more clearly identify strengths and weaknesses regarding a farm's health with consideration of multiple individual metrics (Lightfoot and Noble

2001, Gareau *et al*. 2010, Floridi *et al*. 2011). Of the three farms used to demonstrate the spider plots, variation in biodiversity and ecosystem services patterns is evident. The first farm (Figure 2a) scores well on associated biodiversity indictors, but is lower in planned diversity, while the second farm (Figure 2c) scores high on planned species diversity, but scores lower on associated diversity metrics. In contrast, the final farm (Figure 2e) scores well on a mix of both. For the same three farms, the greatest variation in metrics of ecosystem services (Figure 2b, d and f) is found in the use of continuous living cover, though they score well on other regulating services. All three farms score well in provisioning and cultural services. It is not surprising that different farms excel at different metrics of biodiversity maintenance and ecosystem services; individual landowners have specific goals for their system. A balanced farm scores well on multiple measures but is unlikely to obtain a perfect score on all metrics. Ultimately, consideration of the spider plot allows for a system assessment, while by identifying values of individual metrics, the HFI provides insight for each landowner concerning individual management goals.

Future development and application of the HFI

In the Great Plains Organic case study presented above, we described and illustrated an initial assessment of farms in two ecoregions. This assessment process provided participating farmers initial insight into the patterns of biodiversity and ecosystem services on their farms. By integrating measures of biodiversity with ecosystem services, the HFI improves the ability of farmers to evaluate trade-offs (MA 2005). Yet, farm practices, biodiversity patterns and ecosystem service flows are dynamic and change over time. Thus, it would be more informative to collect and examine metric and index scores on an annual or a semi-annual basis and watch for change and emerging patterns, allowing a landowner to assess and report outcomes of management actions, and adjust future management accordingly. The value of the assessment process would increase in subsequent assessments through a cyclical process of annual data accumulation, assessment and adaptive management. Ultimately, annual assessment would allow farmers to focus on overall trends rather than on microtrends and anomalies.

Farming is a complex adaptive system (Darnhofer *et al*. 2010). Annual assessment (Figure 3) can formalize the ongoing adaptive management processes already inherent in many farm operations by gathering valuable data and insight from applied practices. Assessment at the farm scale

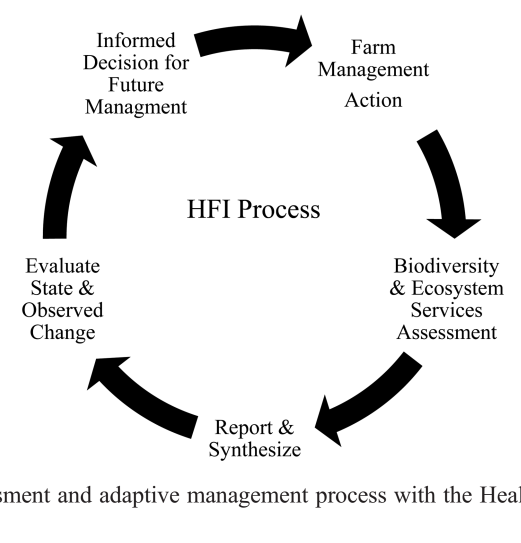

Figure 3. Annual assessment and adaptive management process with the Healthy Farm Index.

will allow for more informed decisions and more effective progress towards shared production and conservation goals through tracking multiple measures of biodiversity and ecosystem services. With the increased information from the HFI and a better understanding of trade-offs and synergies (Bennett *et al*. 2009), a landowner can weigh the costs and benefits of managing for farmland biodiversity more accurately and ultimately improve farm management decisions. Moreover, the HFI provides a basis for incentive programs and/or payment for environmental service schemes that could reward landowners for management of ecosystem services with broader societal interest. Finally, by better engaging farmers, application of the HFI could move farmers towards innovation and use of their farm-specific knowledge to better reach broader societal goals for agriculture and nature conservation.

In the long term and with further development, collaboration and infrastructure, the data collected through the HFI would be applicable at larger scales and for broader research questions. By aggregating individual farm scores within a specific watershed or ecoregion, the HFI can improve and help direct existing research efforts examining trade-offs and synergies in biodiversity and ecosystem services at larger scales. Ideally, individual farm scores would be submitted to, catalogued and organized for use by a central agency. A current model of such a management system is the USGS Breeding Bird Survey programme (Sauer *et al*. 2011). This format will allow researchers, planners and decision makers to have access to the data needed to understand and predict these tradeoffs and synergies. Aggregate datasets from multiple, non-identifiable, farms will improve researcher abilities to identify common patterns as well as numerical and functional changes in the flow of ecosystem services. Such accumulated data could help drive future research and, most importantly, involve farmers in the process.

Conclusions

Agriculture accounts for ∼38% of Earth's total ice-free land (Ellis and Ramankutty 2008, FAO 2007) and is expected to expand and intensify further to meet growing demands (Rands *et al*. 2010). To engage farmers in the global effort in limit negative outcomes of future intensification, we have developed an accessible biodiversity and ecosystem service assessment tool suitable to engage individual landowners in their effort to sustain food production and conserve biodiversity. The HFI provides a framework built around multiple metrics of biodiversity and associated ecosystem services. The HFI provides decision makers with feedback and structure to make informed choices regarding goals across multiple systems. Notably, the HFI does not encourage farmers to maximize biodiversity but rather to restore and maintain a level of diversity beneficial to the farm and local ecosystem and that contributes to local and regional conservation efforts. Ultimately, the vision of ideal on a farm rests with the farmer. Further work is needed to evaluate whether use of the HFI changes farmers' perceptions of the costs and benefits of increased diversity and if farmers change their behaviour through use of the HFI.

Given that planetary thresholds of multiple ecological processes are being crossed (Rockström *et al*. 2009) and that solutions presently remain unclear, local scale analysis and local landowners' involvement will complement global progress towards sustainability (MA 2005, Persha *et al*. 2011). Additionally, given that many policy and economic support mechanisms for farmland environmental programmes are often perceived as rigid (Ahnström *et al*. 2009) and often achieve fewer changes than intended (Kleijn *et al*. 2004), it is clear that better farmer engagement and increased frequency of on-farm ecological research is necessary. Moreover, through consideration of biodiversity and ecosystem services as part of farm assessment, the HFI provides a much needed common language and interface between practitioners of biodiversity conservation and farmers (Berry 2006). Ultimately, both landowners and supporting policy and economic mechanisms (e.g. payments for ecosystem services) are needed to effectively target and implement sustainable management systems locally and globally (Daily and Matson 2008). The HFI provides a timely tool to facilitate management decisions at an individual farm scale and inform research and policy actions at larger scales to achieve mutual goals towards a more sustainable future that maintains long-term farm production, biodiversity and ecosystem services.

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