Article

A Scale-Explicit Framework for Conceptualizing the Environmental Impacts of Agricultural Land Use Changes

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Abstract: Demand for locally-produced food is growing in areas outside traditionally dominant agricultural regions due to concerns over food safety, quality, and sovereignty; rural livelihoods; and environmental integrity. Strategies for meeting this demand rely upon agricultural land use change, in various forms of either intensification or extensification (converting non-agricultural land, including native landforms, to agricultural use). The nature and extent of the impacts of these changes on non-food-provisioning ecosystem services are determined by a complex suite of scale-dependent interactions among farming practices, site-specific characteristics, and the ecosystem services under consideration. Ecosystem modeling strategies which honor such complexity are often impenetrable by non-experts, resulting in a prevalent conceptual gap between ecosystem sciences and the field of sustainable agriculture. Referencing heavily forested New England as an example, we present a conceptual framework designed to synthesize and convey understanding of the scale- and landscape-dependent nature of the relationship between agriculture and various ecosystem services. By accounting for the total impact of multiple disturbances across a landscape while considering the effects of scale, the framework is intended to stimulate and

support the collaborative efforts of land managers, scientists, citizen stakeholders, and policy makers as they address the challenges of expanding local agriculture.

1. Introduction

Many regions of the US are experiencing substantial growth in agricultural production for local markets, a growth spurred by various cultural, economic, and environmental factors such as changing consumer preferences [1]; local and regional food security initiatives (e.g., [2]); the desire to improve rural livelihoods; the perceived social and health benefits of consuming locally-produced food; and an increasing awareness of the environmental impacts and health risks associated with a centralized industrial agricultural system [3,4]. Evidence for the rise in locally-consumed agricultural production includes the increase in local food movements and farmers markets (direct farmer-to-consumer sales) in many parts of the country (Figure 1). The total number of farmers markets increased dramatically, from 1755 in 1994 to 8144 in 2013 [5]; and direct-to-consumer sales more than doubled from $551 million (110,639 farms) in 1997 to $1.3 billion (144,530 farms) in 2012 [6].

An important potential consequence of the growing demand for locally-produced food is an increase in agricultural production, whether in terms of intensity, land-base, or both, in areas that were not major food-producing regions throughout much of the 20th century. Depending on its scale, its spatial distribution in the landscape, and its nature (*i.e.*, type of production practice), agricultural land use change may have important implications for non-food-provisioning ecosystem services currently provided by these regions [7,8]. The environmental trade-offs associated with agricultural production, whether destined for local or distant markets, are well known (see Supplementary Materials). So while an increase in production for local consumption may address a variety of food, health, socioeconomic, and energy issues, it may also result in undesired consequences for other ecosystem services [9]. This is particularly the case if such land use changes involve the production of crops and livestock on current non-agricultural lands of high ecosystem service capacity (e.g., forests, marshes, grasslands).

A greater understanding of the scale-dependent effects of agricultural land use changes on ecosystem services in such regions is needed to formulate science-based recommendations for developing diverse and productive landscapes that minimize the environmental impact of food, fiber, and fuel production across scales. As one US region that exemplifies the expanding local agriculture movement, New England is currently experiencing a range of agricultural land use changes, including conversion of woodland to pasture, cropland, and other agricultural uses (see Supplementary Materials). The observable growing demand for locally-produced agricultural products in the region (Figure 1) assumes additional weight in light of projections for New England to produce 50% of its estimated caloric needs by 2060 [2]. We therefore use the region as the context in which to present a general conceptual framework for understanding the relationship between ecosystem service thresholds and the scale, distribution, and nature of agricultural land use change. Ultimately, the key insights provided by the framework coalesce around the emergent concept of "landscape context", the place- and scale-specific

interaction of independent environmental disturbances, impact dilution mechanisms, and regulating ecosystem services, which we believe lies at the heart of identifying and prioritizing land use strategies for managing the environmental impacts of current and potential future agricultural activity, as well as other forms of anthropogenic disturbance.

Figure 1. The percentage change in the number of US farmers markets, by county, between 2009–2013 (the most recent year for which data are available). Nationwide, 1303 counties (41.0%) showed an increase in the number of direct markets during this time period, compared to a total of 233 counties (7.3%) showing a decrease. The six New England states, considered as a region, exhibit a more pronounced trend than the national average, with 53 of its 67 counties (79.1%) showing an increase in the number of direct markets during this same time period. The graphic was produced with the USDA ERS Food Environment Atlas tool (http://www.ers.usda.gov/data-products/food-environment-atlas/go-to-the-atlas.aspx).
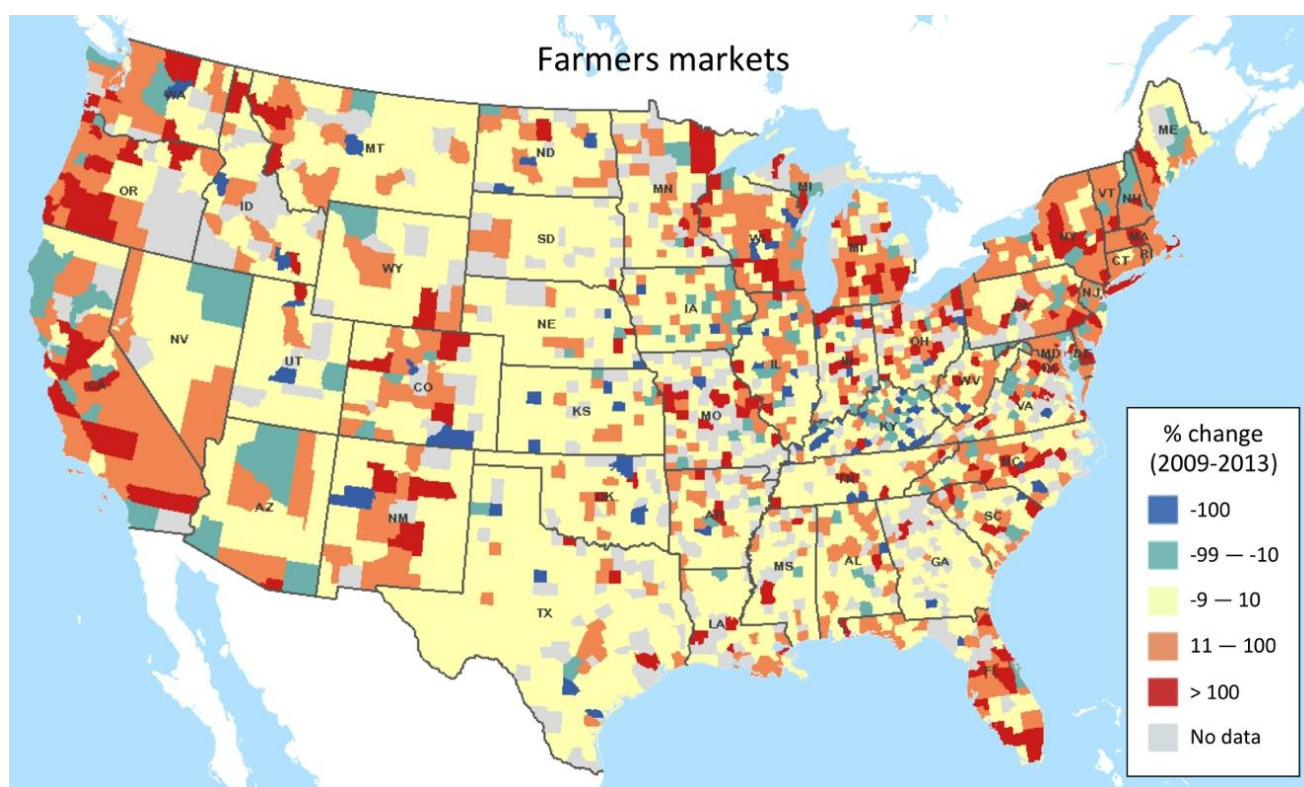
2. A Conceptual Framework for Agricultural Sustainability

Given the current and possible future land use changes in regions of increasing agricultural activity, we propose a conceptual framework (iSIDES) to facilitate understanding and discussion of not only how such changes may impact the flows of energy, nutrients, and water across a landscape, but also where the potential leverage points may exist to manage a landscape so as to ensure the maintenance of critical ecosystem services. Before introducing the iSIDES framework itself, it is worth highlighting its similarities and differences to previous related efforts.

Attempts to conceptualize and model the environmental impacts of various human activities have a long history. In the early 1970's, for example, the IPAT model [10,11] posited that environmental Impact is a function of such factors as Population, Affluence, and Technology. While this was a useful starting

point, integrating multiple factors that influence environmental degradation, IPAT did not explicitly consider the role of ecosystem services in buffering those impacts, nor did it consider the role of scale. It has since been recognized that regulating ecosystem services, as defined in the Millenium Ecosystem Assessment [7], not only mitigate the impact of human activities but that they emerge over spatial scales. While some more recent frameworks have focused on the impacts that one ecosystem service may have on another (*i.e.*, tradeoffs) [12,13], they do not consider how other ecosystem services might limit those impacts. Bennett *et al.* (2006) [9] proposed a typology of ecosystem services where one service impacts another, arguing that these feedbacks must be understood to enhance the overall provision of ecosystem services; and current quantitative models such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) have been developed to understand the interactions and tradeoffs among multiple ecosystem services, with an eye toward economic valuation [14]. While such model studies are extremely useful for understanding interactions, they have not explicitly addressed how ecosystem services emerge over broader spatial scale to mitigate impacts. Nor are such quantitative models, with their attendant complexity, as accessible to non-specialists as earlier conceptualizations were (e.g., IPAT).

The iSIDES conceptual framework proposed here incorporates concepts from the IPAT model, recent work on ecosystem services, and the growing field of ecosystem modeling to explicitly account for the role of scale and ecosystem services capacity to buffer the impact of human activities. Furthermore, it strives to do this while maintaining a conceptual nature accessible to stakeholders outside of the environmental modeling disciplines. In light of these objectives, we suggest that the iSIDES framework, presented in the form of a general quantitative model, is a useful tool not only for understanding the scale-dependent impacts of human activities but also for overcoming the common research-implementation gap (or "knowing-doing" gap [15]) by serving as a conceptual bridge among the various communities engaged in these issues (e.g., academic, political, agricultural, *etc.*).

2.1. Introduction of the iSIDES Conceptual Framework

Figure 2 depicts the scale-dependent impact of a given agricultural practice (or, more generally, any land use), considered in isolation, on a chosen environmental metric. Within this general conceptual framework, hereafter referred to as iSIDES, ecosystem impact is understood to be a function of (1) the chosen spatial Scale of assessment; (2) the local Intensity of the disturbance in question; (3) the Dilution of that disturbance across the landscape; and (4) the mitigating Ecosystem Service capacity of the landscape.

Although the iSIDES conceptual framework is quite general, appropriate for conceptualizing the impact of agricultural land use change on a wide range of ecosystem services, a detailed description of its components will be clearer if grounded in a more specific context. We will therefore proceed to introduce in detail the various components of the iSIDES framework by applying the framework to the specific issue of nitrogen (N) pollution.

Figure 2. The general form of the iSIDES framework, showing the relationship between impact (y-axis) of a human activity on some environmental characteristic and the attenuating detectability of that impact across Scale (x-axis), decreasing from its initial Intensity due to Dilution and regulating Ecosystem Services. The dashed line represents the scale-dependent dilution of the initial impact, while the solid line represents the measurable detection of that impact in the landscape, reduced beyond dilution due to the presence of regulating ecosystem services which accumulate over increasing scales.
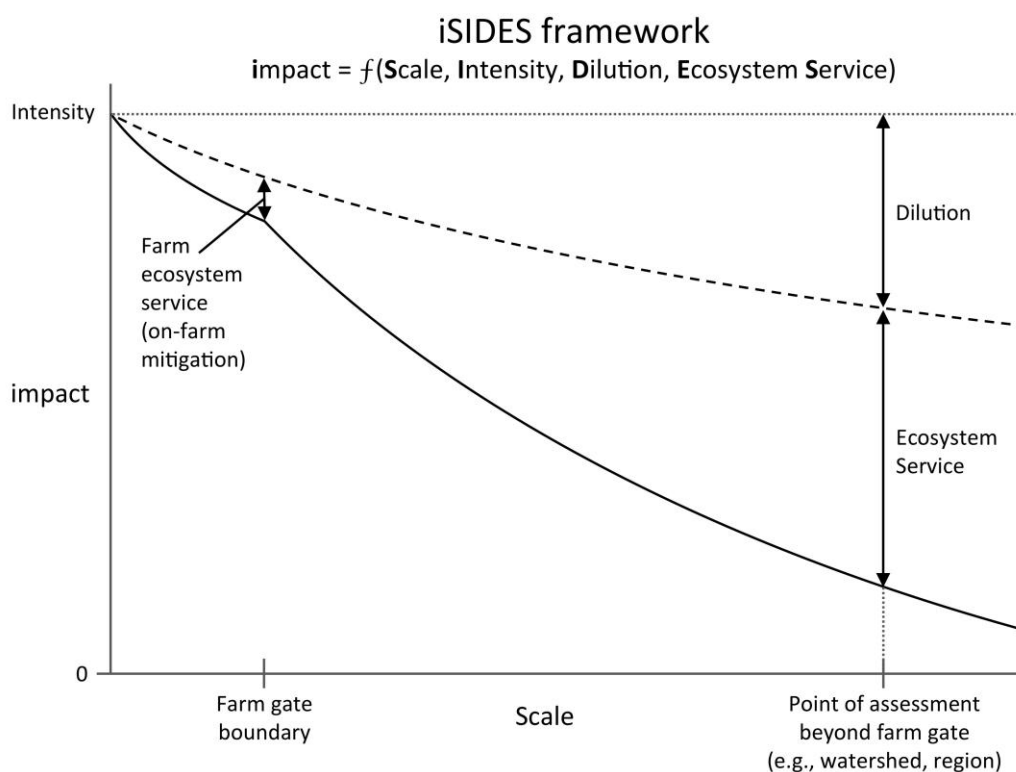
2.2. Explanatory Application of the iSIDES Framework to N Pollution

2.2.1. Background

Nitrogen concentration is one of the criteria used by the Environmental Protection Agency to infer when a water body is impaired [16]. Agricultural activity is a major source of excess reactive N released into the landscape (e.g., via nitrate leaching) [17,18], and natural ecosystem services mitigate its impacts on the environment [19,20]. Examples of ecosystem services relevant to N pollution include transport, uptake with long-term storage, and permanent removal via biological denitrification. Such services emerge across spatial scales, meaning that impacts of agriculture at one spatial scale may not transfer to broader spatial scales, in part because of these services. For example, though a farm may contribute elevated N loads to the streams draining its fields, its impact to downstream systems may be negligible due to a combination of dilution by the remainder of the watershed and denitrification along flow paths (*i.e.*, ecosystem services), provided the farm is situated within a watershed possessing denitrification capacity.

Once mobile N leaves its site of application and intended uptake (e.g., an agricultural field), removal may accumulate slowly along lengthy riverine flow paths or occur in spatially localized hotspots such

as soils, forests, riparian areas, fluvial wetlands, lakes/reservoirs, and floodplains [21]. Nitrogen flux is therefore determined by the accumulation of N sources and the demand for N at a given scale. Thus, as farming activity increases and spreads across a watershed, it is possible for denitrification and uptake to prevent the breakthrough of excess N from that watershed if the demand by aquatic processes along the entire flow path exceeds supply (*i.e.*, uptake capacity is not saturated) [22,23]. While modeling studies demonstrate that denitrification by river systems can remove 20%–50% of N loads on an annual basis, and even more during low flow periods [23–25], the capacity of N regulating ecosystem services will vary regionally and across basins, depending on the locations of sources relative to flow path lengths and the distribution of hot spots of N removal. Demand for N is also tightly linked with the carbon cycle, itself impacted by land use change due to the fact that denitrification requires carbon sources and occurs only where oxygen is first removed by microbial respiration and decomposition of organic matter [26]. For any given watershed, understanding how factors such as the intensity and spatial distribution of N sources, dilution processes, mitigating services, and scale interact offers the opportunity to manage the growth of agriculture in that watershed while minimizing negative impacts to downstream ecosystem services.

2.2.2. Impact

For N (Figure 3), it is biologically meaningful to define impact (y-axis) as the N concentration in surface waters specifically attributable to a given agricultural activity, as measured at some chosen point of observation in the landscape. In the general iSIDES framework, other measures of impact may apply depending on the ecosystem service under consideration. For example, an impact could be a direct effect on an ecosystem service (e.g., fragmentation of wildlife habitat, where the provision of contiguous habitat is understood to be an ecosystem service); or, as in the case of N, an impact may be an environmental indicator (N concentration) of the functional status of an important ecosystem service (e.g., the provision of clean water).

2.2.3. Scale

Since moving water provides the mechanism for transporting N across a landscape, an appropriate definition of Scale (the x-axis, Figure 3) in this case is distance along a flowpath, which roughly corresponds to drainage area. One informative scale at which to assess impact is at the farm boundary (e.g., a stream draining a farm), as this is the point where the measured impact may be attributed to the farm *as a whole*, rather than to a single enterprise within the farming system. Then, because measurable N concentration (as impact) is governed by the interaction of N-producing activities and N-mitigating processes throughout an entire drainage area, another meaningful scale at which to assess impact is the boundary of a watershed (e.g., mouth of a river) within which a farm, a group of farms, or an entire farming region is situated. Depending on the intended application, other scales of assessment may also be considered. Scale is a rich concept within the iSIDES framework, providing not only meaningful points of impact assessment in a landscape, but also serving as the link between an individual farm's activities and the cumulative dilution and ecosystem service capacities of its surrounding landscape.

Figure 3. Demonstration of the iSIDES conceptual model in the context of understanding agricultural impacts to water quality via N pollution. (**A**) Model of river network draining a hypothetical watershed containing five dairy farms. Due to similar management practices, Farms B-E produce equivalent levels of on-farm excess N, while Farm A's relatively more intensive management practices result in twice the production of on-farm excess N. Farms A, B, and E are located at headwaters; and Farm B has enhanced on-farm ecosystem services (90% catchment N removal due to enhanced riparian management, compared to 50% for the other farms); (**B**) Propagation through the watershed of the impact of each individual farm considered in isolation, after accounting for dilution only (dashed lines) and dilution plus N removal accumulated along the flowpath from each farm boundary to the basin mouth (solid lines). In this example, N removal is defined as a constant fraction of inputs within each river reach (*i.e.*, grid cell). The initial impact on water quality (intercept) for each farm is determined by its intensity (excess N), its on-farm mitigation, and its location in the river network, which defines the initial dilution; (**C**) Integrated impact of all farms within the watershed along the longest surface water flow path (*i.e.*, the mainstem, from Farm B to the mouth), accounting for cumulative local impacts, river network structure, dilution, and N removal. Letters indicate where the impact of each farm enters the mainstem, either directly or via tributary; and an example of a designated scale-specific threshold is indicated.
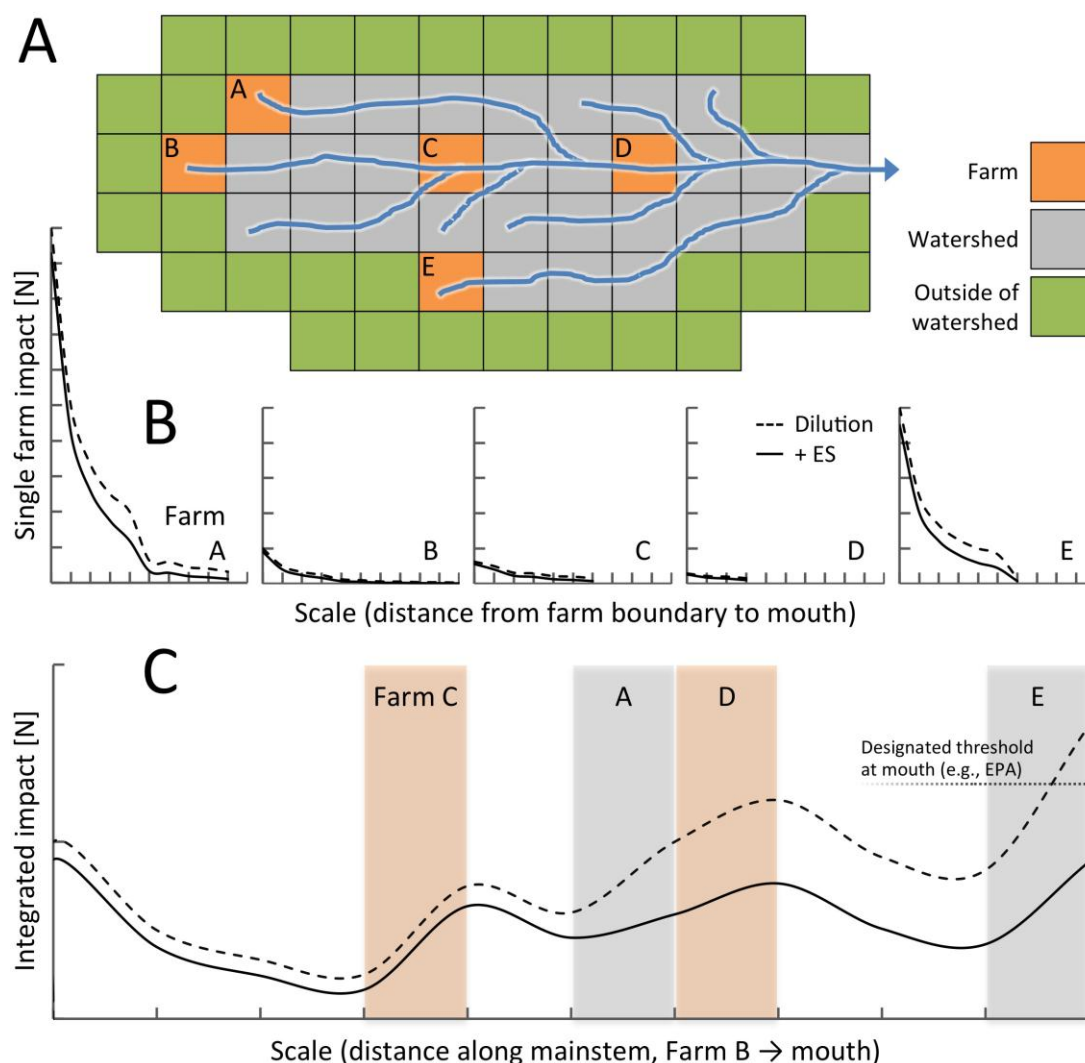
2.2.4. Intensity

The starting value of the impact curve is the peak impact (or Intensity) of a given disturbance, which necessarily occurs at the site of agricultural activity (*i.e.*, a particular location on a particular farm). Figure 3A presents a model of a river network draining a watershed containing five dairy farms, and Figure 3B shows the impact curves of those farms within this hypothetical watershed. In this example, Farms B–E share the same production practices (e.g., grazing cows); Farm A has a more intensive production system (e.g., confined cows); Farm B has enhanced on-farm N mitigation capacity (e.g., due to the presence of well-managed riparian buffers, swales, *etc.*); and Farms A, B, and E are located at headwaters.

Taking the origin of the x-axis to be the farm boundary (*i.e.*, the point where a farm drains into adjacent surface waters), the difference in the intensities of disturbance (y-intercepts) among these farms is attributable to three factors: (1) different agricultural production systems (e.g., a pasture-based dairy operation like Farm E, low intercept, *versus* a more intensive operation like Farm A, high intercept); (2) different levels of on-farm N mitigation (e.g., buffer strips providing on-farm N removal on Farm B *versus* no strips on Farm E); and (3) different scales at which N input to adjacent surface waters occurs (e.g., small stream *vs.* large river).

In general, intensity is determined primarily by the nature of an agricultural activity itself, including the size and spatial distribution of production operations, nutrient inputs, crop/animal uptake, N use efficiencies, and soil disturbances; and intensity will be inherently higher for some activities compared to others (e.g., the relative impact of various tillage regimes on soil loss and soil organic matter accumulation). In addition, factors such as land use conversion can also greatly influence intensity.

2.2.5. Dilution

As one moves away from a point of local disturbance, encompassing broader spatial scales, the measurable impact attributable to that disturbance will decline. Within the iSIDES framework, this purely scale-dependent reduction in impact is referred to as Dilution and is represented by the dashed curves in Figure 3. In the specific case of N concentration, dilution is a function of the drainage area (*i.e.*, aggregate flow volume); in other words, the dashed curves represent the degree to which the initial impact (N concentration = amount of N per unit water) dilutes due to the growing volume of water encompassed by an ever-increasing catchment area. Since ecosystem services not only mitigate but are themselves impacted by land use disturbances, the extent of dilution realized is also a function of the aggregate level of disturbance. That is, as the number and intensities of impacts increase within a watershed, the dilution capacity of that watershed declines, as is currently the case in the Chesapeake, which has undergone considerable eutrophication as a result of widespread agricultural activity and urbanization [27].

As shown in Figure 3B, although Farms D and E are managed in the same manner and therefore have the same on-farm intensities, the detectable impacts of their operations at and beyond their farm boundaries differ due to the locations of those farms in the watershed (*i.e.*, the differential drainage areas at the points of entry into their adjacent surface waters). As a result, the intensity of initial impact, with respect to N concentration in surface waters, is far greater for Farm E than for Farm D; and although dilution acts to eventually reduce the detectable impact of Farm E to levels equivalent to those of

Farm D, Farm E has a greater impact over a broader range of scale. Note that in this example the on-farm dilution of impact is considered negligible and constant across all five farms.

2.2.6. Ecosystem Services

Within the framework, Ecosystem Services mitigate impact beyond the effect of mere physical dilution and are represented by the difference between the impact dilution curve (dashed lines) and the measured impact (solid lines), at a chosen spatial scale (refer to Figure 2). Ecosystem services accumulate with increasing scale; and in the example here, both terrestrial and aquatic ecosystem services, in the forms of N sequestration and denitrification, play a role.

Initially, the impact of an agricultural activity may be mitigated via terrestrial ecosystem services, some of which may be on-farm. For example, though Farms B and E share the same production practices, Farm B reduces the amount of N entering its adjacent headwaters through enhanced on-farm ecosystem services (e.g., 90% removal due to riparian buffers, swales, holding ponds, hedgerows, *etc.* [28]), as compared to Farm E. Once the runoff N leaves a farm boundary and enters surface waters, the measurable impact drops rapidly due to dilution (*i.e.*, a rapid increase in drainage area) and continues to fall due to both continued dilution and accumulated aquatic ecosystem services [29]. Again, while this aquatic ecosystem service could be assessed relative to some criteria at any scale, Figure 3 illustrates its assessment along the main branch, up to the watershed mouth.

2.2.7. Landscape Context

In general, the functional relationship between a farm's impact and scale will resemble a monotonically decreasing, asymptotic curve which captures the aggregate effect of "landscape context" (Dilution + Ecosystem Services) on mitigating impact. Within any defined scale of interest, the presence and nature of a given farm has the potential to influence the landscape context of all other land use activities, activities which in turn define the landscape context of that farm. Despite this inherent complexity, however, it is instructive as a first approximation to assume a context-independent setting in order to visualize the scale-dependent impacts of individual agricultural activities in a given, static landscape (Figure 3B).

2.2.8. Scale-dependent Thresholds

The utility of the iSIDES model lies in the fact that, though we have focused to this point on the simplified, individual impact curves of isolated land use activities, we are able to integrate those curves into a landscape curve, thereby quantifying the aggregated impact of all agricultural activities in concert. Though each farm's individual impact curve is relatively simple, when aligned based on relative location in the landscape, those simple curves can give rise to complex impact functions (Figure 3C). The actual measurable impact in the landscape can therefore be understood to be a highly structured sum of the impact curves of all individual land use activities within the system. In other words, if the impact function of Farm X is:

$$i_x = f(S_x I_x D_x ES_x) \tag{1}$$

then the impact of all n farms in a given landscape, within a domain bounded by the chosen scale of assessment, can be conceptualized as:

$$i_{landscape} = \sum_{x=1}^{n} f(S_x I_x D_x ES_x) \tag{2}$$

While the above summation is a useful first approximation, its indication of linear accumulation may not always be accurate, as when non-linearities occur in ecosystem services (e.g., denitrification rates increase at a slower rate than increasing N concentrations [23,29] (see below and Figure 5 for further discussion).

A scale-dependent threshold is crossed when this integrated impact function for a landscape fails to reach some acceptable level at some critical scale, as indicated in Figure 3C. The acceptable level at the chosen critical scale will depend upon the nature of the impact under consideration and may be set by local regulations or state or regional mandates. Crossing such a threshold is synonymous with creating a collective (*i.e.*, landscape-level) disturbance that exceeds the available mitigating processes (Dilution + Ecosystem Services) at a given scale.

In this example, one management threshold is defined at the watershed mouth, perhaps a critical coastal area. If N concentrations above the threshold level at that scale are detected, it indicates that the collective impact of the integrated landscape exceeds some management-relevant level. Knowing how the individual, underlying land use activities (Figure 3B) contribute to this integrated function (Figure 3C) provides a powerful entry point for making management decisions. Indeed, visualized in this way, it becomes clear that numerous points of leverage may be considered in order to manage the environmental impact of agricultural land use, with actual type of agricultural activity being just one, and of site-specific relevance.

2.2.9. Cross-Scale Impact, Cross-Scale Regulation

As formulated here, the iSIDES framework is novel not only because it explicitly includes the role of regulating ecosystem services in the determination of the level of impact but also because it incorporates a consideration of spatial extent (Scale), which is needed to account for both dilution effects as well as ecosystem services which accumulate over space. Because iSIDES considers scale, it can be applied to a variety of environmental problems that range in scale from local to global; and although the basis of iSIDES is a consideration of the impacts attributable to single, isolated land use activities within a given landscape scenario, by integrating the scale-dependent impacts of all such singly definable disturbances, an approximation of the landscape-level impact attributable to all disturbances in the landscape may be generated. In other words, iSIDES has the potential to model the total impact of arbitrarily large networks of disturbances, while considering the effects of scale.

With the general framework introduced and explained within the specific context of N pollution, we now focus on carbon (C) emissions as a different example which demonstrates how agricultural activity, dilution, ecosystem services, and spatial scale interact, and how the iSIDES framework may be used to conceptualize and prioritize various impact management strategies.

2.3. Application of the iSIDES Framework to C Emissions

iSIDES is a broadly useful conceptual framework, in part because of the flexibility of how one may define the axes, impact and Scale, in light of relevant mechanisms. Due to the highly structured flow paths of reactive N in waterways and the biological relevance of N concentration rather than total N mass, a logical choice for the impact metric in the N example was N concentration. For C, however, it is not the concentration of C emitted but rather the net C flux to the atmosphere attributable to a given agricultural disturbance that is relevant to managing the global C cycle [30].

In the case of C emissions, then, the intercept (Intensity) is the local measure of net per unit area C flux due to the agricultural activity in question (*i.e.*, (total agricultural C emissions - total agricultural C sequestration)/(area ×time)). Before proceeding, it is worth mentioning that the choice of C flux as one measure of impact is not meant to devalue other, more local impacts of C loss, including soil organic matter depletion and its associated fertility and productivity declines. Similar to the N case, Figure 4 presents the impact curves (Figure 4B) for five farms in a hypothetical forested landscape (Figure 4A) over some period of time (e.g., their first year of operation). Due to the fact that C emissions, immediately upon release, become part of the global atmosphere, Scale in this case is represented simply as ever-increasing circular areas centered on the individual farms in question (Figure 4A).

The relatively low intercepts for Farms F, G, and H reflect an intensification scenario in which the net positive C flux is due to intensified production activities (e.g., C release from additional soil cultivation, increased emissions from more frequently used farm equipment, *etc.*). In contrast, Farms I and J represent extensification scenarios, wherein forest is cleared to provide land for agricultural operations. Even though the daily operations of the farms may be the same, the net C fluxes of Farms I and J are orders of magnitude higher than the others due to forest clearing and the initial release of substantial above- and belowground stores of C [31,32]. While the type of agricultural activity and the fate of the cleared wood products (e.g. burned *vs.* utilized as long-lived wood products) must be taken into account when estimating the exact level of emissions due to this sort of agricultural extensification, low mitigation potential as indicated in the curves for Farms I and J is expected due to two reasons: (1) Agricultural fields in the region have significantly lower soil organic C sequestration rates than the forests they may replace [33]; and (2) Even under favorable post-harvest assumptions, significant C release is at best delayed rather than avoided [34].

It is worth noting that this type of analysis, including the labeling of agricultural land use change as "intensive" or "extensive", is very sensitive to the choice of timeframe and is more concerned with the impact of present and future activities rather than historical land use decisions. For example, Farms F, G, and H, here taken as examples of agricultural intensification, were likely converted from forest to agriculture sometime in the past; but the impact on the C balance of those past extensification events are not included in this particular analysis.

Considered at broader spatial scales, the impact of a given agricultural operation on net per unit area C emissions declines primarily due to Dilution (dashed lines); and this dilution of a given farm's impact is extremely rapid due to the fact that the area surrounding each farm increases exponentially as one radiates outward to higher scales. This stands in contrast to the N case, in which drainage area increases in a punctuated manner, with initial flow paths accumulating area roughly linearly until tributaries are met, resulting in a somewhat slower overall dilution effect. Also in contrast to N, there is little, if any,

ecosystem service capacity available to further attenuate impact. Though heavily forested, New England currently sequesters far less than its total C emissions [35], and the region's C sequestration capacity can be considered saturated due to the presence of excess C emissions from the global system, leaving no additional sequestration capacity to offset increased agricultural impacts. As a result, the iSIDES model for C indicates no appreciable difference between the dilution and ecosystem service lines in Figure 4B,C.

Figure 4. Application of the iSIDES framework to conceptualize the impact of increased farming activity on regional carbon cycling. (**A**) Gridded map of hypothetical forested landscape containing five farms. Due to their having similarly intensive agricultural management practices, Farms F, G, and H release equivalent levels of C; Farms I and J, however, release orders of magnitude more C due to agricultural extensification (*i.e.*, forest clearing); (**B**) Impact of individual farm C emissions, as detected at increasingly broader scales, after accounting for dilution only (dashed lines) and dilution plus a marginal increase in C sequestration hypothetically achievable through management of encompassed forestlands (solid lines). In this example, C sequestration is defined as a constant value, independent of the magnitude of C emissions; (**C**) Integrated impact of all farms within the landscape, as one increases scale concentrically from the origin (grid cell labeled "o"), accounting for cumulative local impacts, dilution, and C sequestration. Letters indicate the points at which individual farms are encompassed by the radially-increasing domain.
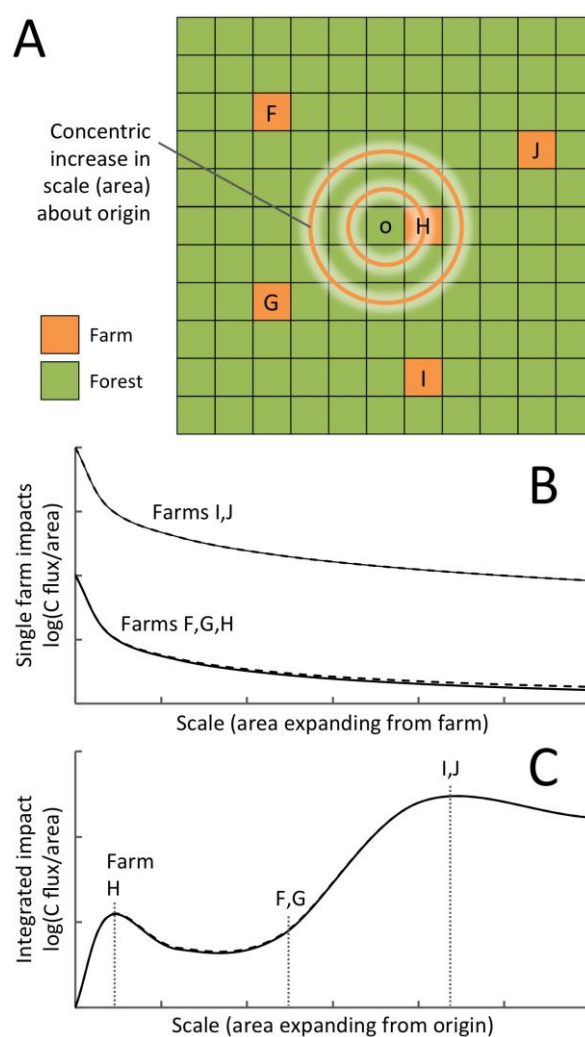
With their precipitous dilution effects, almost indiscernible ecosystem service effects, and widely varying impact scales between the intensification and extensification scenarios, the graphs in Figure 4B reveal some important points. First, the iSIDES framework suggests that management strategies for C flux should focus foremost on Intensity (e.g., minimizing the agricultural conversion of land with large C stores), recognizing that the primary mechanism of impact mitigation is Dilution rather than direct, manageable mitigation via regulating ecosystem services (e.g., C sequestration). This stands in marked contrast to the N example, in which regulating ecosystem services, both on-farm and at higher scales, emerge as potential viable management mechanisms, alongside reduction of Intensity.

Second, while some marginal enhancement of landscape-level C sequestration may be realized (e.g., via optimized forest management practices, reduced tillage, planting trees on abandoned agricultural lands, *etc.*; [35,36]), such increases in regional sequestration capacity are likely to be both relatively small and, due to excess global atmospheric C, independent of increasing C emissions associated with agricultural land use change. This contrasts with the N case, in which the absolute levels of regulating ecosystem services may increase with impact, though perhaps still fall short of compensating for that impact, as long as watersheds are not N saturated. Although currently many watersheds in New England do not appear to be N saturated, some evidence suggests with continued increases in N loading they may eventually approach saturation [23].

2.4. iSIDES and the Kinetics of Regulating Ecosystem Services

Based on the above considerations, we hypothesize that the capacity of regulating ecosystem services to attenuate impacts follows a modified saturating function (Figure 5). Different ecosystem services can be characterized in terms of whether they continue to increase in proportion to impact (Zone I), increase more slowly (efficiency loss, Zone II), increase not at all (Zone III), or decrease (Zone IV). For example, previous work focused on N removal by aquatic ecosystems suggests that, in a watershed with relatively high N loading (the Ipswich, draining suburban Boston, MA), this service is at the lower end of Zone II [23]. More pristine watersheds in the region are likely in Zone I. For C in our example, since sequestration capacity is already exhausted in the region (*i.e.*, currently far more C is emitted than sequestered [37,38]), there is little possibility of increase due to additional impact (Zone III). If anything, the region's C sequestration capacity may decline with increasing impact, particularly under agricultural extensification scenarios in which native landforms are replaced by land use activities with reduced sequestration capacity; hence, ultimately, the possibility of declining services with increasing impact (Zone IV). Similar responses have been demonstrated for changes in provisioning services such as water supply in response to increasing urbanization (e.g., see Figure 8 in [39]).

Establishing the location of place-specific regulating ecosystem services on the proposed kinetics graph (Figure 5) is critical to the accurate application of the iSIDES model and thus to the identification of relevant impact assessment and management strategies. Also, in the case of ecosystem services which lie within the "saturated" zone of the graph (like C sequestration), it is clear that great care must be taken when applying the iSIDES framework not to overestimate a landscape's ecosystem service capacity through double-counting. Unlike the N case, in which the ecosystem service-mitigated impact at the landscape level may be approximated through the sum of the individually mitigated impacts across the landscape, for C the actual landscape level impact is higher than the sum of the individually mitigated

impacts because the marginal increase in C sequestration capacity is fixed and does not scale with impact. This, along with the fact that dilution is essentially the sole mechanism of mitigation, makes C emissions inherently a higher-scale issue than N pollution.

Figure 5. Fundamental to the application of the iSIDES framework is an understanding of the kinetics of the regulating ecosystem service under consideration (*i.e.*, the manner in which increasing impact, due to agricultural land use change or other pressures, will likely affect an ecosystem service under specified conditions). In this suggested typology, resembling a modified saturation curve, an ecosystem service may be classified as falling within one of four zones: (I) Robust: the service increases linearly with increasing impact; (II) Challenged: the increase in service declines with increasing impact; (III) Saturated: there is no service response under increasing impact; or (IV) Deteriorating: the service declines under increasing impact.
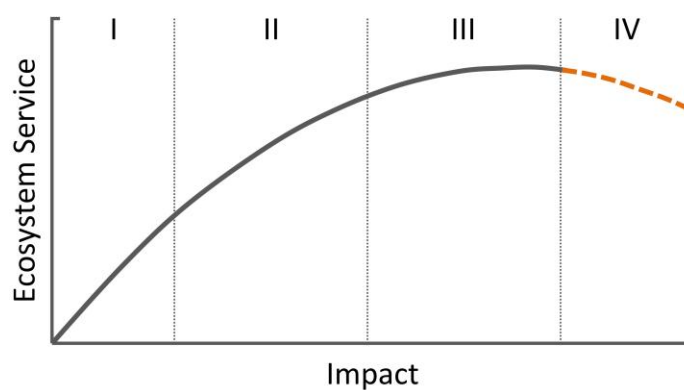
3. Conclusions

3.1. Policy and Management Implications

As New England and other regions navigate the growth of agricultural production in landscapes dominated by non-agricultural land cover, the conceptual framework presented here suggests that "landscape context" (Dilution + Ecosystem Services) will be a major determinant of the environmental impacts of such expansion. Landscape context, defined by the physical location of agriculture in the landscape, the use type and legacy of adjacent lands, and the kinetics of the ecosystem service under consideration (Figure 5), is an emergent, scale-dependent concept with noteworthy implications.

First and foremost, since environmental sustainability (*i.e.*, not crossing ecosystem thresholds) is a systems-level property of a *landscape*, managing for sustainable agricultural growth is a challenge to be met both by land managers and by land-use planners beyond the farm-scale. While in theory an individual farm could be managed in such a way that minimal ecosystem impact is exported beyond the farm gate (*i.e.*, agricultural sustainability could lie solely within the domain of the producer), the land requirements for the on-farm ecosystem services needed to accomplish this could either be reasonable (e.g., in the case of N pollution) or could severely limit the agricultural productivity of a given piece of land (e.g., in the case of C sequestration), with consequences both in terms of farm economic

sustainability as well as the need for bringing more, and perhaps less desirable, land into production to meet regional demand (*i.e.*, extensification).

In practice, then, whether a scale-dependent ecological threshold is breached is a function not simply of a given agricultural practice but of the larger landscape in which the practice resides [40]. Because all agricultural activities inherently entail some level of ecological disturbance, agricultural sustainability is both a farm-scale management and broader-scale landscape design challenge. The iSIDES framework is a useful tool not only for visualizing the potential, highly place-specific impacts of agricultural land use change on various ecosystem services, but also for highlighting the non-uniformity of those impacts on different ecosystem services, a key insight in the identification and prioritization of land use management strategies.

3.2. A Path Toward Sustainable Agricultural Land Use Change

The conceptual framework developed here poses several hypotheses relative to the challenge of increasing agricultural production without crossing critical ecological boundaries, including:

(1) Agricultural sustainability is only partially about agricultural production practices themselves. For some ecosystem services, it is also to a significant extent about the management of the broader landscape within which agricultural activities are situated. To avoid exceeding certain important environmental thresholds, solutions may require a combination of minimizing the intensity of agricultural activities; boosting on-farm ecosystem services; and coordinating/regulating larger patterns of agricultural and non-agricultural land use at higher scales (watershed, state, region, *etc.*), for example through the development of results obligation incentive or subsidy programs which take a farm's landscape context, not just its practices, into consideration.

(2) In New England, where the current landscape is dominated by forests (*i.e.*, native landforms with certain high ecosystem service capacities), it is critical that we gain a better understanding of the contributions of the region's forested lands to buffer environmental disturbances inherent to agricultural activity. This includes understanding the role of forests in diluting and mitigating impacts as a function of land use legacy, management, and site characteristics. In other regions faced by similar challenges, such questions need to be answered with regard to other native landforms (e.g., perennial grasslands). Given the immense role of New England's forests with regard to nutrient cycling and water quality, intensification (or "land-sparing") approaches to increasing agricultural production may not only apply to the conservation of environmental services in tropical and other high diversity regions but may also be of critical importance in some temperate regions as well, a conclusion often not considered in previous analyses [4,41].

(3) The two examples outlined here, one for N pollution and one for C emissions, indicate that different, and possibly conflicting, strategies may be appropriate for managing the impacts of agricultural land use change on various ecosystem services. Differences in impact proliferation mechanisms, dilution processes, and the functional relationships between impact and regulating ecosystem service capacity raise the possibility that simultaneous management for a suite of diverse ecosystem services may be unachievable, necessitating an understanding of trade-offs and a clear prioritization of management goals. While our framework suggests that increasing regional agricultural productivity through intensification of existing farmland appears preferable in terms of C emissions,

intensification in the absence of commensurate on-farm and watershed-scale mitigation strategies could in fact lead to increased quantities of reactive N in the environment, relative to extensification scenarios. This is an important nuance to the "land sparing" intensification approach to increasing agricultural productivity discussed in many recent studies (e.g., [4]) and highlights the need to define the nature of the iSIDES impact functions for all relevant ecosystem services in a given location in order to develop effective agricultural expansion strategies. In addition to identifying trade-offs, such an approach could also reveal potential synergies in ecosystem services to be gained by various land use strategies.

As the examples here are intended to demonstrate, we believe the iSIDES framework to be a management-relevant tool to integrate and conceptualize key considerations necessary for developing strategies for managing ecosystem services in the face of increasing agricultural pressures. While not all ecosystem services may be amenable to this framework, it should prove useful to researchers, policymakers, and other stakeholders when conceptualizing issues as diverse as nutrient cycling, pollinator habitat, wildlife corridors, soil erosion, water conservation, and others (Table 1). In fact, although here we apply the framework exclusively in the context of agricultural activity, we believe it to be general enough to be applied to other land-use pressures as well.

Table 1. Examples of other applications of the iSIDES framework, beyond those of N pollution and C emissions outlined in this paper (first two rows). These other examples, along with possible definitions for each of its parameters, illustrate the potential generality of the framework as a tool for conceptualizing the scale- and landscape-dependent effects of increasing agricultural production on a wide range of important environmental and agricultural metrics.

Effect of agricultural land use change on...	The iSIDES Framework				
	impact	Assessment Scale	Intensity	Dilution	Ecosystem Services
N pollution	N concentration	Watershed	Concentration of mobile N due to farm operations	Function of drainage area	Denitrification and N uptake
C emissions	C flux/area	Region	C release due to land conversion and farm operations	In all directions, rapid	C sequestration
Plant diseases	Disease severity	Region	Inoculum level (ppm)	Function of pathogen mobility and distribution of hosts	Reduced selection for and spread of agriculturally-relevant virulences due to heterogeneous plant populations
Native pollinators	Population density	Farm-to-region	Yield loss due to insufficient pollination	Function of background population density	Pollinator refuges

Table 1. *Cont.*

Effect of agricultural land use change on...	The iSIDES Framework				
	impact	Assessment Scale	Intensity	Dilution	Ecosystem Services
Large mammals	Habitat fragmentation	Region	Edge-to-habitat ratio	Function of habitat continuity	Habitat quantity
Soil erosion	Rate of soil loss/area	Watershed	Rate of soil loss due to land conversion and farm operations	Function of drainage area	Soil stabilization
Water flow	Increased flooding	Watershed	Run-off, as % of precipitation	Function of drainage area	Infiltration and soil water storage/groundwater recharge

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Author Contributions

All authors were involved in the development of the iSIDES conceptual framework and the writing of the manuscript. All authors read and approved the final manuscript.

Supplementary Materials

Supplementary materials can be accessed at: http://www.mdpi.com/2071-1050/6/12/8432/s1.

Conflicts of Interest

The authors declare no conflict of interest.

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