

Review

Impacts of Agricultural Management Systems on Biodiversity and Ecosystem Services in Highly Simplified Dryland Landscapes

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Abstract: Covering about 40% of Earth's land surface and sustaining at least 38% of global population, drylands are key crop and animal production regions with high economic and social values. However, land use changes associated with industrialized agricultural managements are threatening the sustainability of these systems. While previous studies assessing the impacts of agricultural management systems on biodiversity and their services focused on more diversified mesic landscapes, there is a dearth of such research in highly simplified dryland agroecosystems. In this paper, we 1) summarize previous research on the effects of farm management systems and agricultural expansion on biodiversity and biodiversity-based ecosystem services, 2) present four case studies assessing the impacts of management systems on biodiversity and ecosystem services across highly simplified dryland landscapes of the Northern Great Plains (NGP), USA, 3) discuss approaches to sustain biodiversity-based ecosystem services in drylands, and 4) present a conceptual framework for enhancing agricultural sustainability in the drylands through research, policy, economic valuation, and adaptive management. An analysis of the land use changes due to agricultural expansion within the Golden Triangle, a representative agricultural area in the NGP, indicated that the proportion of land conversion to agriculture area was 84%, 8%, and 7% from grassland, riparian, and shrubland habitats, respectively. Our results showed this simplification was associated with a potential reduction of pollination services. Also, our economic analysis projected that if 30% parasitism could be achieved through better management systems, the estimated potential economic returns to pest regulation services through parasitoids in Montana, USA alone could reach about \$11.23 million. Overall, while dryland agroecosystems showed a significant loss of native biodiversity and its services, greater pest incidence, and a decrease in plant pollinator networks, these trends were moderately reversed in organically managed farming systems. In conclusion, although land use changes due to agricultural expansion and industrialized farming threaten the sustainability of dryland agroecosystems, this impact can be partially offset by coupling ecologically-based farming practices with adaptive management strategies.

Keywords: agricultural expansion; biodiversity-based ecosystem services; farm management systems; Golden Triangle; Northern Great Plains

1. Background

Drylands are regions with an aridity index (ratio of precipitation to potential evapotranspiration) of 0.05 to 0.65 [1]. Covering about 40% of Earth's land surface and sustaining approximately 38% of global population, drylands are key agricultural production regions [2,3]. Despite their ecological, economic, and societal importance, the sustainability of drylands is heavily limited by land use changes due to agricultural expansion, geographical constraints, elevated temperature, reduced moisture, variable rainfall, drought, wildfires, and environmental degradation [4–6]. Furthermore, the loss of species diversity due to land use changes and industrialized agriculture seriously threatens the sustainability of major ecosystem services provided by drylands, such as pollination and pest regulation [7,8].

Drylands have considerable agricultural and societal value, as crops of global importance including barley, cotton, olives, millet, sorghum, and wheat as well as domesticated animals including cow, camel, goat, horse, and sheep originated from these regions [9]. However, industrialized farming and climatic variability have resulted in serious ecological consequences including a reduction in biodiversity due to habitat loss, degradation of soil and water quality, changes in surface energy and water balances [10], as well as production losses in drylands [11]. However, drylands have received relatively little research attention [12,13], limiting the available information on the impact of land use intensification on biodiversity, ecosystem services, and sustainable management. For example, previous studies assessed the impacts of agricultural management systems on associated biodiversity including weeds, pollinators and their services, pollination networks, or pest regulation, but were conducted in more diversified and less arid systems in Europe [14–16], California [17–19], and the mid-western US [20,21]. Further, a recent global synthesis of 89 crop systems on the role of biodiversity and biodiversity-based ecosystem services to crop productions does not include the world's agriculturally important dryland regions [22], such as the Northern Great Plains and the Pacific Northwest of North America [23]. Hence, there is a dearth of research into the impacts of agricultural expansion and management systems on biodiversity and ecosystem services in simplified dryland landscapes [24–26]. However, these systems are projected to expand to 48% of global land by 2025 due to the changing climate [27]. Understanding the impacts of farm management systems and land use changes on biodiversity and ecosystem services is thus essential to sustain dryland ecosystems in the face of global climate change, population growth, and increased food and fiber demands.

In this paper, we focus on the impact of agricultural management systems on biodiversity and ecosystem services in highly simplified dryland landscapes (i.e., the landscapes in semiarid regions, with an aridity index of 0.2–0.5 [23,28], that are heavily dominated with intensive non-irrigated agriculture), with an emphasis on the Northern Great Plains (NGP), one of the leading dryland agricultural regions in the world [29–33]. Specifically, we combine the results from previous research into pollinators and parasitoid responses to management systems with additional data on the extent of landscape conversion and the economic impact of ecosystem services to highlight potential avenues to enhancing agricultural sustainability in drylands. Because of the scarcity of information, we were precluded from conducting a formal systematic analysis of previous research on biodiversity and ecosystem services in highly simplified dryland agricultural landscapes, such as those in the Northern Great Plains. We hope this review will help future researchers fill the existing knowledge gaps.

2. A Case Study of Land Use Changes due to Agricultural Expansion in the Drylands of the Northern Great Plains

Once dominated by grassland, shrubland, and riparian habitats, the NGP dryland has experienced agricultural expansion after European settlement, heavily simplifying the landscape into annual cropping systems. We quantified the extent of such landscape simplification in the Golden Triangle region of Montana, a representative section of the NGP dryland, by assessing the biophysical setting (BpS) data at a spatial unit of $\sim 1 \text{ km}^2$ from the LANDFIRE (a US government's Landscape Fire and Resource Management Planning Tool) products [34] to represent major habitats: shrubland, grassland, conifer, riparian, hardwood, and sparse vegetation. The BpS layer was developed to represent

vegetation patterns that may have been dominant prior to Euro-American settlement. This layer is based on present-day biophysical environments and the approximation of historical ranges of natural disturbance regimes. The current human land-use layers (developed area, roads, and agriculture) were overlaid on these modeled historical layers to estimate aerial extents of natural habitat loss within the Golden Triangle. The total change in area of each habitat was determined by dividing the difference in area of selected classes between historical and present-day ecosystem area by total area of each ecosystem class.

Our study showed that the riparian habitat had the highest loss to land conversion (-76%), followed by grassland (-73%), shrubland (-62%), conifer (-17%), and sparse (-11%) habitats (Figure 1). The proportion of land converted into agricultural production has been estimated from grassland (84%), riparian (8%), and shrubland (7%) habitats (Figure 1). The agricultural expansion experienced in this area resulted in small remnant fragments of natural habitats within a matrix of monoculture crops, resulting in a highly simplified landscape where the remaining undisturbed natural habitats support a higher biodiversity compared to the intensified crop fields. For example, a 12-ha inventory of a remnant mixed-grass prairie conducted in 2009 near Havre (48.490° N, 109.802° W), Montana revealed a higher diversity of forbs, grass, and shrub species (Table 1) compared to previous studies conducted in croplands of this region [35]. This reduction in biodiversity, in turn, would constrain the ecosystem services they provide.

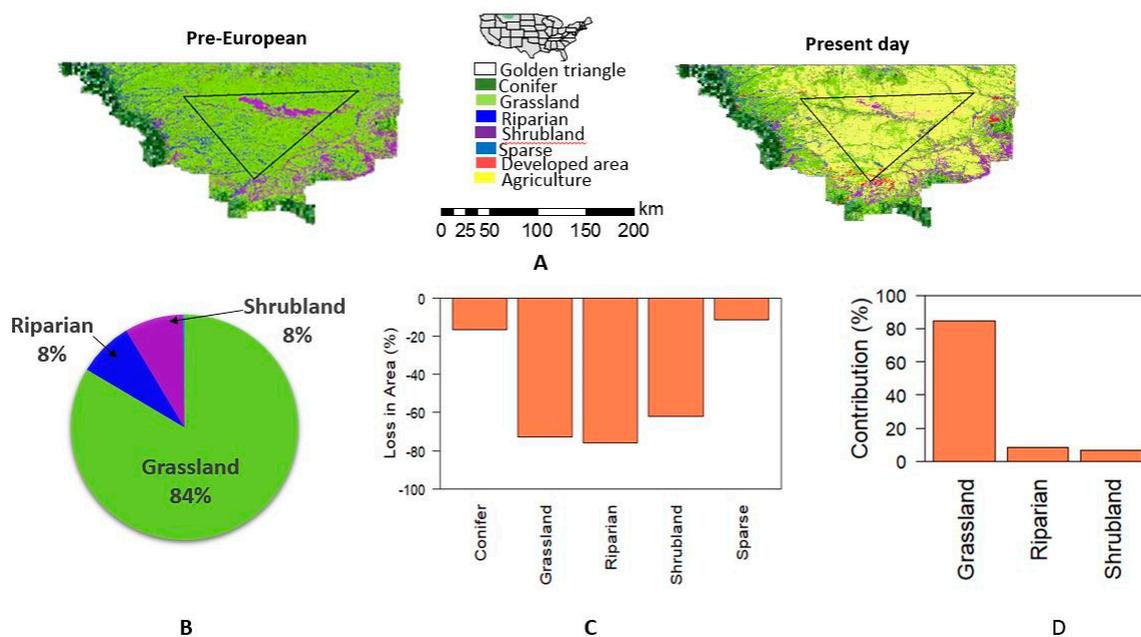


Figure 1. Land use changes due to agricultural expansion in the Golden Triangle area of the Northern Great Plains: (A) pre-European settlements versus present-day ecosystem types, (B) proportion of ecosystem types prior to European settlements, (C) relative reduction in area due to the agricultural expansion of ecosystem types from pre-European settlements to the present-day, and (D) contribution of each pre-European settlement habitat type to agricultural land.

Table 1. List of plant species identified in 2009 from a 12-ha mixed native prairie relict site near Havre, Montana (Welch, unpublished data).

Plants	Family
Graminoids	
<i>Koeleria macrantha</i> (Ledeb.) J.A. Schultes	Poaceae
<i>Hesperostipa comata</i> (Trin. & Rupr.) Barkworth	Poaceae
<i>Pascopyrum smithii</i> (Rydb.) A. Love	Poaceae
<i>Pseudoroegneria spicata</i> (Pursh) A. Love	Poaceae
<i>Muhlenbergia cuspidata</i> (Torr. ex Hook.) Rydb.	Poaceae
<i>Calamovilfa longifolia</i> (Hook.) Scribn	Poaceae
<i>Poa sandbergii</i> Vasey	Poaceae
<i>Schizachyrium scoparium</i> (Michx.) Nash	Poaceae
<i>Bouteloua gracilis</i> (Willd. ex Kunth.) Lag. ex Griffiths	Poaceae
<i>Nassella viridula</i> (Trin.) Barkworth	Poaceae
<i>Carex filifolia</i> Nutt.	Cyperaceae
* <i>Bromus tectorum</i> L.	Poaceae
* <i>Bromus japonicus</i> Thunb.	Poaceae
* <i>Agropyron cristatum</i> (L.) Gaertn.	Poaceae
* <i>Poa pratensis</i> L.	Poaceae
Forbs	
<i>Pediomelum argophyllum</i> (Pursh) J. Grimes	Fabaceae
<i>Phlox hoodii</i> Richardson	Polemoniaceae
<i>Antennaria neglecta</i> Greene	Asteraceae
<i>Heterotheca villosa</i> (Pursh) Shinnars	Asteraceae
<i>Cirsium undulatum</i> (Nutt.) Spreng.	Asteraceae
<i>Penstemon grandiflorus</i> Nutt.	Scrophulariaceae
<i>Plantago elongata</i> Pursh	Plantaginaceae
<i>Lygodesmia juncea</i> (Pursh) D. Don ex Hook.	Asteraceae
<i>Comandra umbellata</i> (L.) Nutt.	Santalaceae
<i>Thermopsis rhombifolia</i> (Nutt. ex Pursh) Nutt. ex Richardson	Fabaceae
<i>Gaillardia aristata</i> Pursh	Asteraceae
<i>Achillea millefolium</i> L. var. <i>occidentalis</i> DC.	Asteraceae
<i>Potentilla glandulosa</i> Lindl.	Rosaceae
<i>Allium textile</i> A. Nelson & J.F. Macbr.	Liliaceae
<i>Linum lewisii</i> Pursh	Linaceae
<i>Tetraneuris acaulis</i> (Pursh) Greene	Asteraceae
<i>Sphaeralcea coccinea</i> (Nutt.) Rydb.	Malvaceae
<i>Vicia americana</i> Muhl. ex Willd.	Fabaceae
<i>Liatris punctata</i> Hook.	Asteraceae
<i>Nothocalais cuspidata</i> (Pursh) Greene	Asteraceae
<i>Symphotrichum ericoides</i> (L.) G.L. Nesom var. <i>pansum</i> (S.F. Blake) G.L. Nesom	Asteraceae
<i>Machaeranthera pinnatifida</i> (Hook.) Shinnars	Asteraceae
<i>Ratibida columnifera</i> (Nutt.) Wooton & Stand	Asteraceae
<i>Opuntia polyacantha</i> Haw.	Cactaceae
<i>Packera plattensis</i> (Nutt.) W.A. Weber & Á. Löve	Asteraceae
<i>Lycopodium</i> L., spp.	Lycopodiaceae
Bryopsida (Limpr.) Rothm., spp.	
* <i>Medicago sativa</i> L.	Fabaceae
* <i>Melilotus officinalis</i> (L.) Lam.	Fabaceae
* <i>Sinapis arvensis</i> L. ssp. <i>arvensis</i>	Brassicaceae
* <i>Tragopogon pratensis</i> L.	Asteraceae
** <i>Taraxacum officinale</i> F.H. Wigg	Asteraceae
** <i>Urtica dioica</i> L.	Urticaceae

Table 1. Cont.

Plants	Family
Shrubs	
<i>Symphoricarpos occidentalis</i> Hook.	Caprifoliaceae
<i>Artemisia ludoviciana</i> Nutt.	Asteraceae
<i>Artemisia dracunculoides</i> L.	Asteraceae
<i>Artemisia longifolia</i> Nutt.	Asteraceae
<i>Artemisia frigida</i> Willd.	Asteraceae
<i>Krascheninnikovia lanata</i> (Pursh) A. Meeuse & Smi	Chenopodiaceae
<i>Artemisia cana</i> Pursh	Asteraceae
<i>Rosa arkansana</i> Porter	Rosaceae
<i>Rosa acicularis</i> Lindl.	Rosaceae
<i>Gutierrezia sarothrae</i> (Pursh) Britton & Rusby	Asteraceae

* invasive, exotic; ** invasive, both native and exotic subspecies.

3. Impacts of Agricultural Management Systems on Biodiversity and Ecosystem Services in Highly Simplified Drylands

Flowering crops and weeds growing in arable lands may provide food resources to beneficial insects such as bees, parasitoids, and generalist predators for a limited amount of time. In the resource-depleted environments that dominate highly simplified agricultural landscapes, non-crop habitats are required to provide season-long nesting grounds, food resources, and refugia from disturbances [36,37]. However, with the degree of high landscape simplification observed in the NGP resulting from agricultural expansion, the ecosystem benefits provided by non-crop habitats could be either significantly reduced or absent. In this section, we summarize findings of our ongoing research aimed at evaluating the impacts of management systems on plant diversity and its importance on parasitoid abundance, pollination networks, and bee colony success in the simplified agricultural landscape that dominates the NGP. Our overall goal was to examine the consequences of management systems on biodiversity and ecosystem services in highly simplified dryland agricultural landscapes. This information will, in turn, allow us assess farm management strategies that can be helpful to sustain biodiversity in dryland agroecosystems. To our knowledge, these studies represent the first attempt to assess the impact of the associated floral biodiversity on pollinator communities and ecosystem services across the Northern Great Plains.

3.1. Management Systems and Associated Plant Diversity

Access to adequate food resources such as pollen and nectar as well as shelter from adverse conditions is essential for the survival and reproduction of beneficial insects such as predators, parasitoids, and pollinators [31,38,39]. In highly simplified and biodiversity-depleted agroecosystems, weedy forb species could represent a viable source of pollen and nectar. To evaluate the impacts of farm management systems on weed communities, between 2013 and 2015, we established 55 m transects within each of nine conventional and nine organic spring wheat fields located in the simplified agricultural landscape of Big Sandy, Montana, USA (see [24–26] for details).

Compared to the remnant prairie (see Section 2; Table 1), we found a lower abundance and diversity of plants in the crop fields, regardless of farming system (Table 2). However, similar to Pollnac et al. [35], we observed increased weed species abundance and diversity in organic systems when compared to conventional ones. Even so, except for a single species (*Artemisia frigida* Willd.) that was present in a low abundance in an organic field, none of the 10 species of perennial shrubs found in mixed grass prairie was observed in crop fields. Similarly, 27 native and 3 exotic forb species that were present in the remnant prairie were not observed in either conventional or organic crop fields. Crops growing as volunteer weeds were the main contributors to forb diversity in the sampled organic crop fields. Overall, these results indicate that land use changes due to agricultural expansion and management systems adversely influence plant biodiversity; however, volunteer crop plants and other forbs contributed to the plant diversity observed during the growing season in organic crop fields.

Table 2. List of weed taxa with their relative abundance observed in organic and conventional wheat fields between 2013 and 2015. The table is adopted from Adhikari and Menalled [26].

Weed Taxa	Percent Composition (Overall)	
	Conventional	Organic
<i>Amaranthus blitoides</i> S. Watson	<0.01	<0.01
<i>Amaranthus retroflexus</i> L.	<0.01	0.47
<i>Arabidopsis thaliana</i> (L.) Heynh.	-	<0.01
<i>Artemisia frigida</i> Willd.	-	<0.01
<i>Avena fatua</i> L. *	4.71	4.70
<i>Bassia scoparia</i> (L.) A.J. Scott	0.07	0.14
Brassicaceae sp.	-	0.04
<i>Bromus arvensis</i> L. *	0.08	<0.01
<i>Bromus tectorum</i> L. *	8.40	0.20
<i>Buglossoides arvensis</i> (L.) I.M. Johnst.	-	<0.01
<i>Carthamus tinctorius</i> L.	-	0.69
<i>Chenopodium album</i> L.	-	7.43
<i>Chenopodium murale</i> L.	-	<0.01
<i>Cirsium arvense</i> (L.) Scop.	2.55	<0.01
<i>Descurainia pinnata</i> (Walter) Britton	<0.01	0.03
<i>Descurainia sophia</i> (L.) Webb ex Prantl	-	0.01
Fabaceae sp.	-	<0.01
<i>Fagopyrum esculentum</i> Moench	-	0.03
<i>Helianthus annuus</i> L.	<0.01	2.72
<i>Hordeum jubatum</i> L.*	5.03	0.04
<i>Lactuca serriola</i> L.	0.12	0.43
<i>Lens culinaris</i> Medik.	-	0.15
<i>Leptochloa fusca</i> (L.) Kunth *	<0.01	-
<i>Medicago lupulina</i> L.	-	0.01
<i>Medicago sativa</i> L.	0.89	3.50
<i>Melilotus officinalis</i> (L.) Lam.	-	0.07
<i>Monolepis nuttalliana</i> (Schult.) Greene	-	<0.01
<i>Pisum sativum</i> L.	-	1.08
<i>Poa annua</i> L.*	<0.01	-
<i>Polygonum aviculare</i> L.	0.01	0.14
<i>Polygonum convolvulus</i> L.	0.13	6.70
<i>Pseudoroegneria spicata</i> (Pursh) *	0.81	-
<i>Salsola kali</i> L.	2.72	36.15
<i>Salvia reflexa</i> Hornem.	0.10	0.01
<i>Setaria viridis</i> (L.) P. Beauv. *	0.13	0.05
<i>Silene latifolia</i> Poir.	-	<0.01
<i>Sinapis arvensis</i> L.	-	2.23
<i>Sisymbrium altissimum</i> L.	-	0.04
<i>Solanum triflorum</i> Nutt.	-	<0.01
<i>Taraxacum officinale</i> F.H. Wigg.	0.34	0.04
<i>Thlaspi arvense</i> L.	-	1.31
<i>Tragopogon dubius</i> Scop.	<0.01	-
<i>Trifolium</i> sp.	-	<0.01
<i>Triticum aestivum</i> L. *	-	3.50
Unknown (dicot) sp.	<0.01	0.81
Unknown (grass) sp. *	<0.01	0.03
<i>Vaccaria hispanica</i> (Mill.) Rauschert	-	0.63
<i>Vicia americana</i> Muhl. ex Willd.	<0.01	0.43

* grasses.

3.2. Management Systems, Pest Infestation, Parasitoid Abundance, and Pest Regulation Services

With an annual economic value in the United States of USD 4.5 billion [40], biological control-based pest regulation is an important ecosystem service for agriculture [41–43]. For example, the annual economic loss to wheat growers across NGP due to *Cephus cinctus* Norton (wheat stem sawfly), a native pest species [44], has been estimated at USD 350 million [45]. In this region, biological control of *C. cinctus* by two endemic specialist parasitoids, *Bracon cephi* (Gahan) and *B. lissogaster* Muesebeck, represents a pest regulation service to wheat growers [46,47] that can effectively reduce yield losses by 19% when specific harvest outcomes are considered [48]. These parasitoids are highly specialized, and *C. cinctus* is their only known host [49,50].

Diversified cropping systems enhance *C. cinctus* parasitoid populations [25,51,52], ultimately helping to manage *C. cinctus* and thus reduce yield loss from infested fields. However, the conventionally-managed wheat–fallow rotations that dominate the dryland sections of the NGP can have negative impacts on parasitoid populations and effectiveness [48,53]. In a study assessing the effects of landscape composition and wheat cover on infestation by the native *C. cinctus* and parasitism by its endemic specialist parasitoids, Rand et al. [54] found the highest *C. cinctus* (wheat stem sawfly) infestation but lowest parasitism in conventionally grown wheat fields within Montana’s relatively dry Golden Triangle, a primary winter wheat production region when compared to other studied areas across North Dakota and South Dakota, USA. Surprisingly, they reported no correlation between increased natural grassland habitat and *C. cinctus* infestation or parasitism. The plausible explanations for this could be a) a lack of sufficient natural enemies to control pest population, b) insufficient natural habitat for supporting natural enemy populations needed for pest control, and/or c) an excessive reliance on farming practices that are unfavorable to the natural enemy communities (e.g., use of pesticides) [55–57].

Agricultural management systems include not only determining which crops to grow and how to manage farms (e.g., conventionally or organically), but also when to plant a crop that could potentially have differential effects on pest infestation. To assess whether the timing of plantation affects pest infestation, we compared the role of winter (i.e., fall-planted) and spring (i.e., spring-planted) wheat crops on the parasitism of *C. cinctus* using sample data collected from 1998–2011 in Montana wheat fields ($n = 1945$) across more intensively managed agricultural landscapes in the Golden Triangle (see Figure 1) and outside ($n = 1895$) (reported in [48]). Infestation in spring wheat fields outside the Golden Triangle was double that of spring wheat fields inside the region, while the opposite was true for winter wheat: the infestation was 20% lower outside the Golden Triangle (Table S1). Interestingly, numbers of parasitoids were nearly half in spring wheat fields, and the surviving *C. cinctus* larval population was lower in the Golden Triangle than the outside region. For winter wheat, however, parasitism was nearly twice as high in the Golden Triangle as outside, but the percentage of stems with surviving *C. cinctus* larvae was greater in the Golden Triangle. Overall, winter wheat inside the Golden Triangle was more exploited by *C. cinctus* and will benefit considerably from farming practices that favor increased parasitoid abundance and survivorship. With a total of 0.93 million hectares of land planted in winter wheat and 1.21 million hectares in spring wheat in 2016 in Montana only [58], the differences in *C. cinctus* populations associated with winter and spring wheat is a determining factor in parasitoid abundance [25]. Our result also indicates that outcomes related to ecosystem services provided by parasitoids that specialize on *C. cinctus* should be evaluated separately for each growing season (i.e., winter and spring), as suggested in Bekkerman and Weaver [48].

Further, to evaluate the impact of cropping systems on *C. cinctus* parasitism, we collected winter wheat samples between 2013 and 2015 from tilled organic and no-till conventional fields of a highly simplified landscape at Big Sandy, Montana, USA (see details in [25]). We then compared infestation by *C. cinctus* and subsequent parasitism across farming systems. Our results showed that, relative to conventionally-managed fields, organic management was associated with a 75% lower *C. cinctus* infestation and a quadrupling of parasitism by endemic braconids (Table 3). These results indicate that while simplified landscapes have relatively limited floral resources to parasitoids, by enhancing

alternative sources of pollen and nectar via increased weed diversity [36,46], organic fields partially offset the negative effects of landscape simplification on pest regulation in the drylands of the NGP.

Table 3. Number of stems infested with *Cephus cinctus*, *C. cinctus* infested stems with parasitoids, stems cut by *C. cinctus*, and total number of stems observed in tilled organic and no-till conventional winter wheat fields in Big Sandy, Montana between 2013 and 2015. The table is adopted from Adhikari et al. [25].

Farming Systems	Infested Stems	Parasitoids	Cut Stems	Total Stems Observed
Conventional	684	37	359	1835
Organic	195	54	48	969

To estimate the potential economic returns to pest regulation services (i.e., biodiversity-based ecosystem services) of *C. cinctus* parasitoids, we developed counterfactual analyses based on the model and data in Bekkerman and Weaver [48] to consider three parasitoid population scenarios: zero parasitoids (no parasitism), 2x parasitoids (doubling the number of parasitoids present in original data), and parasitoids in 30% of all infested stems (which represents a reasonable population target, similar to observed populations reported above for organic fields [25]). Relative to a base-case scenario of sample means, each counterfactual analysis calculated the potential additional stem-level yield gains or losses from higher or lower parasitoid populations for winter and spring wheat, and then used ten-year average Montana production and price data to approximate state-level impacts. The results showed that because base-case parasitoid populations are relatively small, completely eliminating or doubling parasitoids had only modest state-level economic impacts. However, if parasitism reached a realistic optimum (i.e., 30%), estimated production losses were reduced significantly by 21%, representing an economic gain of USD 11.23 million (Table S2). As our study shows, a target of 30% parasitism could be achieved through better management systems, such as transferring and incorporating the desirable features we observed in organic winter wheat systems into larger, more conventional farming practices.

3.3. Management Systems and Bee Colony Success

Bees (Hymenoptera: Apoidea, Apiformes) are key agents in pollinating about one-third of the leading global crop species [59,60]. However, a suite of anthropogenic stressors and perturbations including reduced regional floral resources, landscape simplification, habitat fragmentation, and exposure to pesticides, parasites and pathogens contribute to the declining bee biodiversity [61–63]. The NGP is a key agricultural region for cereal, forage, pulse, and oilseed production; however, the impact of available floral resources on bee colony success mediated by agricultural expansion and management systems is unknown.

By putting 60 mini-colonies of eastern bumble bee (*Bombus impatiens* Cresson) at six conventional and six organic spring wheat fields over two growing seasons (2014–2015) across the abovementioned simplified agricultural landscape in Big Sandy, Montana, USA, we assessed the effects of farming systems on bee colonies' relative growth rate, fecundity, worker lipid content and wing wear (see details in [24]). We found that colonies' relative growth rate and fecundity were larger in weedier organic fields than in conventional fields and were positively associated with floral resources (see details in [24]). Similarly, workers from organic fields had lower wing wear and marginally greater body lipid content, indicating that foraging distances are smaller in organic than in conventional fields [24]. Overall, these results indicate that by increasing *B. impatiens* colony success and individual worker condition, the greater floral resources observed in organic systems can provide better biodiversity-based ecosystem services even in a highly simplified agricultural landscapes such as the ones that dominate the NGP.

3.4. Management Systems and Bee–Flower Networks

The decline in plant diversity due to conventional agricultural practices and landscape simplification observed across the NGP can ultimately impact the structure of pollinator communities and, in turn, plant–pollinator networks [61,64]. Despite the ecological and economic importance

of pollinators [59,65], there is limited information on their abundance and diversity in the dryland agroecosystems of the NGP. To assess the extent to which cropping systems impact plant–pollinator networks in dryland settings, we compared bee–flower interaction networks between conventional and organic fields in the simplified agricultural landscape at Big Sandy, MT during 2013–2015 [66].

By recording the identity and frequency of bee–flower interactions during 20 minutes of observations (51 hours in total) on each of nine conventional and nine organic fields between 2013–2015, we constructed bee–flower networks [66,67]. Our results indicated that bee–flower interactions were either absent or extremely simplified in conventionally managed fields. In contrast, because of the greater forb flower density and diversity observed in organic fields, bee–flower interactions were more common in these systems (Figure 2). However, the observed networks were far less connected when compared with those observed in more botanically diverse landscapes [68–70]. The study indicates that highly simplified agricultural landscapes in the NGP maintain relatively impoverished bee–flower interaction networks; however, by supporting more floral resources, diversified organic farming helps to increase plant–pollinator interactions.

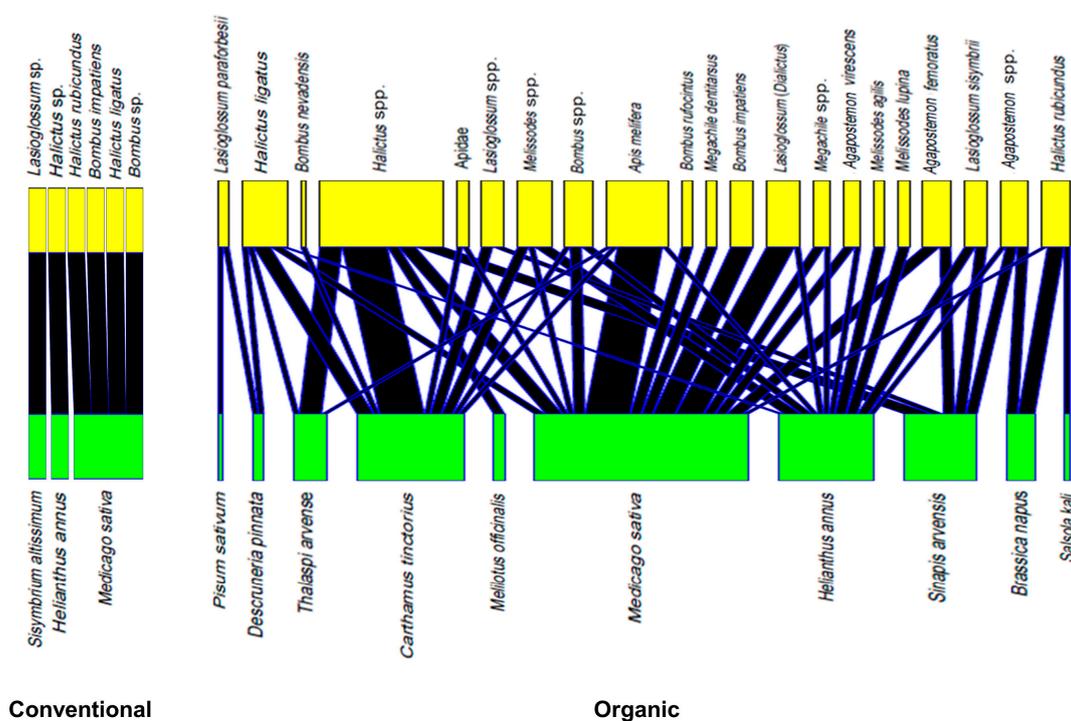


Figure 2. Bee–flower interaction networks from conventional and organic wheat fields in the Golden Triangle area, Montana, USA. The top yellow horizontal bars represent bee taxa and the bottom green horizontal bars represent forb species in the networks. The black lines connecting bee taxa and forb species represent interaction links (visits), and the thickness of these lines corresponds to the strength of the interactions between two species. Note: All observation data were pooled across months (June–August), fields (nine for each system), and years (2013–2015) to construct the networks in each system and show the general patterns of which bee and forb species were present in the landscape during our study. The figure is adapted from Adhikari [66].

4. Discussion: Enhancing the Sustainability of Dryland Agroecosystems

While a majority of previous studies assessing the impacts of land use changes due to farm management systems and agricultural expansion on plant diversity, pollinator communities and services, pollination networks, and pest regulation were conducted in diversified mesic systems [14,19,21,71], a limited amount of research has been conducted on highly simplified drylands. This review fills this gap by assessing biodiversity and biodiversity-based ecosystem services in

the context of dryland agroecosystems. Our results underscore the importance of diversifying agroecosystems to enhance populations of beneficial insects including parasitoids and pollinators. Specifically, our results showed that most habitat types in the NGP have been converted into agricultural production after European settlement, significantly reducing non-crop habitats. While we observed a significant economic contribution of insect parasitoids on reducing crop production loss due to pests, effects of non-crop habitats alone in agricultural fields on biological pest regulation are not guaranteed, but instead depend on farming systems, landscape composition, local climatic factors, and their interactions [66,67,69].

Our studies indicated that, even in highly simplified dryland landscapes, the increased biodiversity observed in organic systems can help to enhance ecological networks and biodiversity-based ecosystem services [24–26,66]. These results are in line with others that have shown that greater plant diversity supported by more complex landscapes enhance natural enemy populations including parasitoids and predators of crop pests [42,72] and augment natural pest regulation [40], thereby reducing the heavy reliance on pesticide applications. For example, Rusch et al. [73] found that natural pest control in crop-dominated simplified landscapes was 46% lower than in more complex landscapes. Similarly, tachinid parasitoids [74] and predaceous syrphid fly larvae [75] in California's agroecosystems were positively associated with semi-natural habitats surrounding farms and negatively associated with crop cover across the landscape. Additionally, landscape diversification in drylands may also increase the provision of other services such as water quality, soil fertility development, climate stability, greenhouse gas sequestration, and aesthetics [28,76]. Hence, practices that promote increased crop and weed diversity, such as the diversification of organic farming systems, support these parasitoids so that they can provide a significant economic contribution or ecosystem services by reducing crop production loss due to pests.

Conservation biological control (i.e., the maintenance of beneficial insects through habitat management in croplands) has received significant attention in the last two decades [41,72]. Relatively undisturbed and uncultivated lands within agricultural landscapes can provide refugia for natural enemies and generalist predators supporting pest management [41,72]. As this review shows, this concept can be used to conserve other beneficial insects such as pollinators. Floral resources present in crop fields may be abundant for a short period, making them usually insufficient during the early and late seasons that are critical in bee life cycles for establishing colonies and producing offspring [77,78]. The increasing abundance and diversity of native plant communities and expanding natural habitats may enhance pollinator communities within agricultural landscapes which, in turn, could result in enhancing crop yields [21,79]. Conservation strategies for beneficial insects may include allocating 20–30% of agricultural landscape to uncultivated habitats, planting native flowers in hedgerows, and including forb crops in crop rotations [42,80,81]. Our results [24–26,66] indicate that combining these strategies with organic farming practices can help enhance beneficial insects' nesting and foraging habitats, consequently bolstering their populations, and allowing growers to further reap the benefits of pest regulation and pollination.

The presented results and complementary studies [82–85] help produce a framework of adaptive management in drylands to enhance dryland agricultural resilience and sustainability. Our framework includes first identifying causes (e.g., agricultural expansion) and impacts (e.g., loss of biodiversity) of land use changes as the fundamental step (Figure 3). Second, assessing and evaluating biodiversity and its services and potential disservices would help identify and prioritize the proper farm management systems in the region. Third, identifying proper policies and extension programs based on monitoring and evaluation of ecosystem assessments could effectively help redesign agricultural landscapes to help conserve natural habitats. Fourth, adaptive management strategies are key to continuously evaluating and adjusting new policies and approaches that are informed by research results and experiences [28,86,87].

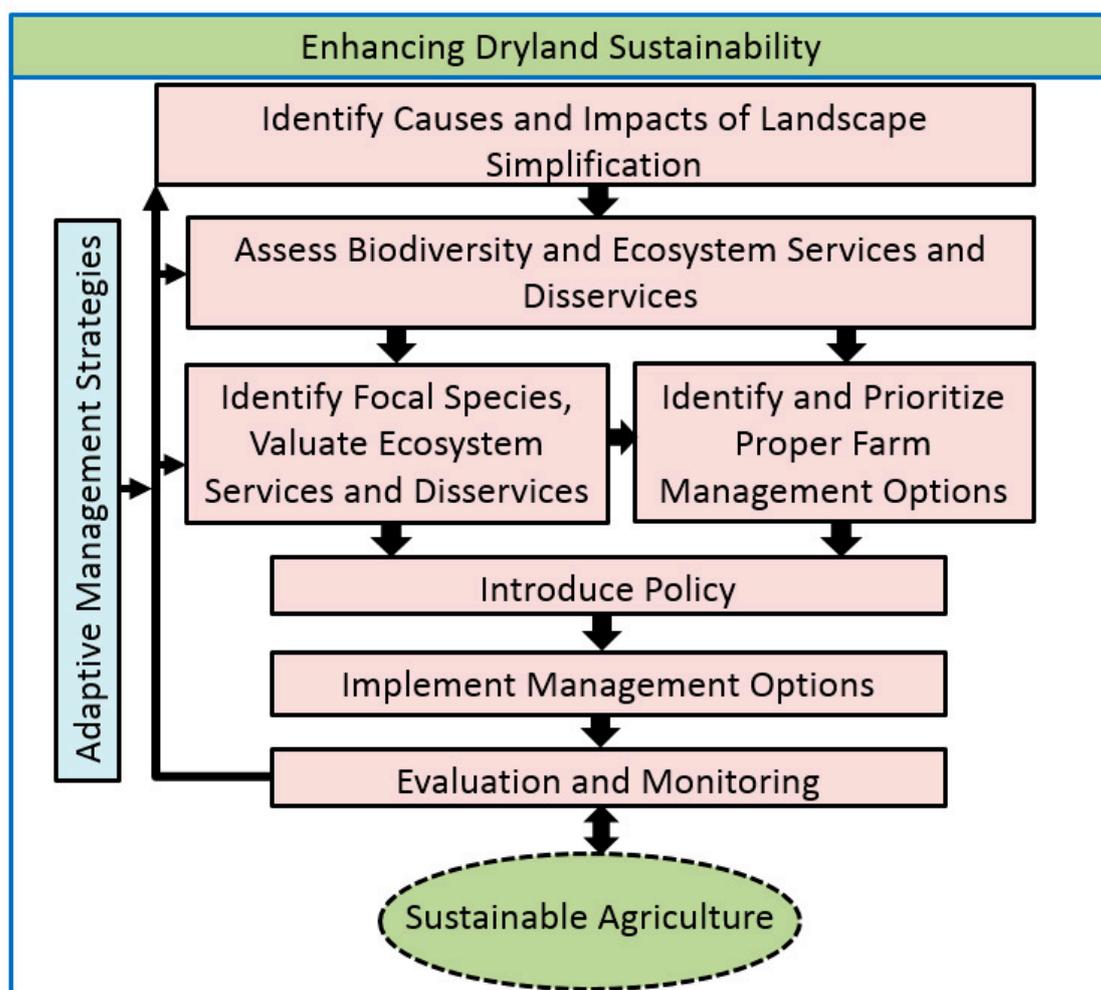


Figure 3. A conceptual framework for enhancing agricultural sustainability in the drylands through research, policy, economic valuation, and adaptive management.

5. Conclusions

While land use changes, overexploitation of resources, climatic variability, pollution, and species invasion have resulted in biodiversity loss and serious ecological consequences globally [88], dryland ecosystems and their associated human populations are more vulnerable than other ecosystems [28,89,90]. Due to their worldwide occurrence, drylands, despite several climatic and environmental constraints, provide significant ecological and socio-economic benefits to local, regional, and global populations [91–93]. However, if current farm management practices associated with modern agricultural intensifications are continued, they may further jeopardize drylands, and thus increase economic and ecological uncertainty for the growers [94]. Overall, the NGP region showed a significant expansion of agricultural lands after European settlement and illustrate consequent losses of biodiversity and associated impacts. Also, conventionally managed farming systems that rely on monoculture and off-farm synthetic inputs such as nitrogen fertilizers and herbicides contribute to the reduced biodiversity and hence biodiversity-based ecosystem services. Natural and human-induced processes coupled with socioeconomic factors are responsible for the habitat loss and biodiversity reduction observed in the dryland sections of the NGP [95,96]. To mitigate these losses, priority should be given to the adoption of more appropriate management practices such as diversified organic production that relies on crop rotation, multiple cropping, and avoidance of off-farm synthetic inputs. Similarly, proactive farming practices in drylands should aim at increasing spatial and temporal habitat

heterogeneity [97–99]. Along with crop diversification across the landscape, the preservation and restoration of natural habitats is required to enhance pest regulation in the dryland agroecosystems [73].

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/11/11/3223/s1>, Table S1: Cephus cinctus infestation and its parasitoid abundance in spring and winter wheat fields inside more intensively managed landscape of Golden Triangle, Montana, USA and outside. Table S2: Estimated pest regulation service values by parasitoids of Cephus cinctus in Montana, USA. To estimate the values, a counterfactual analysis was done on C. cinctus infested spring and winter wheat stems and parasitoids presence on infested stems with four scenarios: base case, zero parasitoids, 2x parasitoids, and parasitoids in 30% of infested stems.

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