Monarch Butterfly Habitat Quantification Tool Specifications Document

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Version 1.0

ACKNOWLEDGEMENTS

The Monarch Butterfly Habitat Quantification Tool is being developed for the Monarch Butterfly Habitat Exchange. It is the product of Environmental Defense Fund, Environmental Incentives, and the Monarch Lab at the University of Minnesota. The expert insight and guidance provided by the Monarch Lab has been essential to the development of this document and the HQT in general.

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Related Products

The Monarch HQT consists of a set of products, each with different purposes and audiences.

- **Monarch HQT Specifications Document** (this document): describes the scientific approach for quantifying impacts and benefits to monarch habitat for use in the Monarch Butterfly Habitat Exchange. It includes a description and definition of the attributes measured, methods of evaluating suitability for each attribute, and supporting documentation (e.g., peer-reviewed literature, gray literature, expert opinion).
- **Monarch HQT User's Guide**: provides detailed instructions for assessing monarch habitat using the Monarch HQT. It is intended for experienced field biologists but may be used by knowledgeable landowners or managers. Refer to the appropriate version for the region in which the assessment is conducted.
- **Monarch HQT Credit Project Calculator**: an Excel-based tool that computes habitat suitability, functional acres and monarch yield based on parameters measured at the site. Refer to the appropriate version for the region in which the assessment is conducted.

Review of the HQT Specifications documentation is not required to apply the Monarch HQT.

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Contents

INTRODUCTION

The Monarch Habitat Exchange (Exchange) is an incentives-based program intended to promote restoration and protection of monarch habitat across the U.S. The program supports farmers, ranchers and other land managers to create, enhance and manage/maintain monarch habitat. Participants can generate “credits” based on the suitability of monarch habitat on their property and uplift resulting from restoration and conservation actions. Conservation organizations, philanthropists, corporations, and others can purchase credits to fund monarch conservation and mitigate risks to monarch populations.

The Monarch Habitat Quantification Tool (HQT) is used by the Exchange to evaluate habitat and estimate benefits to monarchs. An HQT is a science-based approach to assessing habitat suitability and conservation outcomes for a species. The purpose of an HQT is to facilitate efficient resource allocations for species conservation and incentivize landowners to participate in species conservation. An HQT can be used to assess a site through time, compare different sites or management alternatives, and track program-wide progress towards important conservation outcomes.

The purpose of the Monarch HQT is to measure change in monarch butterfly habitat condition within the context of the Monarch Butterfly Habitat Exchange, track changes to meaningful habitat variables through time, and report progress towards regional program goals.

The objectives of the HQT include:

1. Inform site selection
2. Measure changes in habitat condition resulting from management actions
3. In part, facilitate the estimate of payments to landowners for achieving conservation outcomes
4. Monitor ongoing project performance
5. Track and report progress towards regional program goals

No existing tools fulfill these objectives for the Monarch Butterfly Habitat Exchange, and so the Monarch HQT was created.

MONARCH CONSERVATION STATUS

Monarchs engender a great deal of public interest (Diffendorfer et al. 2014; Gustafsson et al. 2015), and thus serve as a flagship species that promotes engagement in conservation among many audiences. In 2014, the U.S. Fish and Wildlife Service (USFWS) was petitioned to list the North American population of monarchs as threatened under the Endangered Species Act (Center for Biological Diversity et al. 2014) and after a positive 90-day finding, the USFWS subsequently initiated a status review.

There are clear indications that the eastern population of monarch butterflies (*Danaus plexippus*) warrants conservation concern. The status of this population is traditionally assessed by documenting the area in the Mexican wintering grounds occupied by trees covered by monarchs, and this area has declined at a rate averaging ~0.89 ha/year (Oberhauser et al. 2016), with the lowest two population sizes recorded during the winters of 2013–2014 and 2014–2015, when the areas occupied were only 0.67 and 1.13 hectares, respectively (Rendón-Salinas & Tavera-Alonso, 2015). The White House has announced a goal to increase this population to 225 million butterflies by 2020, which will occupy an area of ~6 hectares in the Mexican overwintering grounds (Vilsack and McCarthy 2015).

The western monarch population has also declined to an extent comparable to the eastern population. Censuses of the western overwintering population began in 1997 and showed a population size of 1.2 million monarchs, with historical accounts suggesting a population of at least this size before these counts began (Pelton et al. 2016, Monroe et al. 2016, Center for Biological Diversity et al. 2014). However, in recent years, population numbers have remained low, not having gone over 275,000 individuals since 2001 and currently at approximately 74% below historic levels (Pelton et al. 2016).

The decline of monarch butterflies is likely attributable to the additive effects of several causes. The primary cause for the eastern population decline is generally accepted to be the loss of milkweeds due to the use of glyphosate on herbicide-tolerant crops (Pleasants and Oberhauser 2013). The Midwestern U.S. (and specifically the subsection known as the Corn Belt) was once an important source of milkweed habitat for monarchs; milkweed grew abundantly in agriculture fields and surrounding areas, and rates of monarch use of these milkweeds suggest that the vast majority of monarchs that migrated to Mexico each year originated in corn and soybean fields (Oberhauser et al. 2001). The adoption of glyphosate tolerant crops has devastated milkweed abundance in much of this landscape (Pleasants and Oberhauser 2013). Other causes for monarch declines include habitat loss due to land use change, non-target effects of insecticide use, and overwintering habitat loss and degradation (summarized by Stenoien et al. 2016). There are several studies that document monarch mortality from disease and natural enemies (summarized in Altizer et al. 2011, Altizer & de Roode 2015, De Anda & Oberhauser 2015, Oberhauser et al. 2015), and the current and impending effects of global climate change pose potential threats to breeding habitats (Lemoine 2015), overwintering habitats (Ramirez et al. 2015), and monarchs themselves (Nail et al. 2015, Nail & Oberhauser 2015).

CONSERVATION GOALS & OBJECTIVES

In order to reduce monarch extinction risk and maintain the annual migration, restoration and maintenance of sufficient monarch habitat must be achieved (Pleasants 2016). While the eastern subpopulation accounts for a majority of the monarch population, the conservation of both the eastern and western subpopulations are considered equally important by the Exchange. Conservation targets are established for both subpopulations to reflect differences between the two subpopulations, however it should be noted that there is likely some intermixing of the two populations (Pyle 2015). These targets provide measurable goals for monarchs to which the Exchange will contribute; however, specific objectives reflect range-wide needs for monarchs, and are not specific targets for the Exchange.

Monarch Habitat

Goal: Restore and maintain high-quality, diverse, and distributed monarch habitat throughout the breeding range of monarchs in the continental U.S, including the eastern and western subpopulations.

Objective (Eastern subpopulation): Establish and maintain 1.6 billion milkweed stems by 2020, primarily in the South Central and North Central regions (Pleasants 2016), as compared to 2016 levels.

Objective (Western subpopulation): TBD. There is considerable uncertainty in defining strategies appropriate for conservation of monarchs in the West, and thus proposing conservation targets. In general, habitat should be created or restored where it is historically appropriate and where risk to monarchs, such as through pesticide exposure, is minimal. Protection of existing habitats a high priority although it is clear that additional habitat is needed to reverse population declines.

Monarch Population

Goal: Restore monarch populations to reduce extinction risk.

Objective (Eastern subpopulation): Reach and maintain an average of 6 hectares occupied by the overwintering population in Mexico by 2020. A recent analysis by Semmens et al. (2016) predicted that, if attained, this population target will reduce the risk of eastern population quasi-extinction over 10–20 years by more than 50% for all minimum population thresholds considered. However, achieving this goal over a longer timeframe may be more realistic.

Objective (Western subpopulation): Reach and maintain 1.2 million monarchs as counted in the Western Monarch Thanksgiving Count (WMTC) by 2025. This would restore monarch populations to levels counted in 1997 when censusing first began (Pelton 2016). This objective may be modified as conservation planning continues in the West.

APPROACH TO QUANTIFYING HABITAT QUALITY

The Exchange requires a defensible means for assessing habitat suitability, quantifying benefits to monarch habitat from restoration and conservation actions, and communicating achievements to investors and other stakeholders. The assessment procedure must be simple and efficient and, at the same time, accurate enough to inspire stakeholder confidence and precise enough to detect meaningful change.

To meet these objectives, we developed an HQT using a modified Habitat Evaluation Procedure (HEP). In this approach, we relate habitat characteristics (indicators) to observed and expected demographic response variables using empirical data and expert opinion. These relationships are translated into suitability indices (SIs) for each indicator, such that a given level of any habitat characteristic can be interpreted as a level of suitability for monarchs. Suitability indices for individual indicators are combined to develop a Habitat Suitability Index (HSI). Habitat suitability refers to the ability of habitat to sustain monarchs, support reproduction, and contribute to the overall population relative to other habitats. Two HSIs (a breeding and a foraging HSI) are developed to evaluate the ability of a site to provide for breeding and foraging requirements. The breeding and foraging HSIs can be interpreted individually to understand the suitability of the site for each type of habitat use.

The HSIs are combined using a weighted sum model to produce an overall HSI, which is multiplied by the area of the site to calculate functional acres (analogous to habitat units in the original HEP procedure). Functional acres are intended to reflect the relative contribution of a site to overall carrying capacity (equilibrium density) and the probability that individuals or their progeny occupying that site contribute to the winter population. The current focus of monarch conservation efforts is to increase the capacity of North American habitat to support monarch production and survival (i.e. the number of monarchs surviving at the end of a breeding season); thus, it is important that the HQT reflect the contribution of any assessed habitat towards those efforts. Any given site can contribute to the winter population by supporting monarchs during spring and early summer breeding and migration, mid to late summer breeding, and autumn migration. However, the scoring model has not been validated in the sense of comparing model outputs to long-term measurements of monarch demographic parameters or population trends. Data to facilitate such model validation are not available currently, and the development timeline of this HQT precludes gathering these data. When properly applied, however, the scoring models and their indicators should describe the relative contribution of a site towards conservation targets.

Key Terms

Habitat Suitability – the ability of habitat to sustain monarchs, support reproduction, and contribute to the overall population relative to other habitats.

Habitat Evaluation Procedure (HEP) – an approach to estimating habitat suitability developed by the USFWS.

Suitability Index (SI) – defines the relationship between a habitat characteristic (e.g., milkweed abundance) and the suitability of that habitat for monarchs.

Habitat Suitability Index (HSI) – a model of habitat suitability which describes the relative value of a specific habitat to monarchs.

Habitat Quantification Tool (HQT) – a tool for assessing, ranking, comparing, and monitoring habitat over time and across different sites.

Functional Acres – calculated by multiplying the habitat suitability (as a percentage) by the size of the habitat patch (measured in acres).

Monarch Wildlife Habitat Evaluation Guide (WHEG) – a tool for assessing monarch habitat used by the NRCS.

The Monarch HQT is intended to focus land managers, investors, and other stakeholders on restoring and protecting high quality and diverse monarch habitat across the contiguous U.S. The Monarch HQT prioritizes characteristics of monarch habitat that are both (1) primary drivers of monarch habitat suitability and (2) within the influence of decision makers (e.g., land managers). Predation, competition, extreme weather, and climate change, among other factors, all affect monarch population levels, but they will not be assessed because they are largely outside of the influence of land managers. The Monarch HQT should not be confused with more robust demographic models such as those under development by the Monarch Conservation Science Partnership (MCSP, e.g. Oberhauser et al. 2016). However, data collected during application of the HQT may be input into such demographic models to estimate changes to monarch habitat and population levels over time.

To promote collaboration and learning, we strive to maintain compatibility with ongoing data collection, habitat evaluation, and demographic modelling efforts, including NRCS Monarch Wildlife Habitat Evaluation Guides (WHEGs) and the MCSP Integrated Monitoring Framework, to the extent possible. Thus, data collected during HQT habitat assessments can be used to evaluate the availability of monarch habitat on a broad scale (a goal of the MCSP Integrated Monitoring Framework), and future iterations of the HQT can be parameterized using data from the MCSP Integrated Monitoring Framework. We also reviewed existing methods for evaluation of habitat for other pollinators, thus allowing land managers to evaluate restoration and enhancement efforts for multiple species without unnecessary repetition of effort. The objectives of those efforts are different than the objectives of the HQT, and so some deviation was necessary to increase sensitivity to desired management actions and discriminate between sites of similar quality.

APPLICATION OF THE HQT

While the data collected during a habitat assessment using the HQT and the outputs of the scoring model should be valuable to any assessment of monarch habitat, the HQT is designed to be applied within the context of the Monarch Exchange. The priorities of the Monarch Exchange are to restore, enhance, and preserve habitat on agricultural lands (e.g., farms and ranches) and corridors (e.g., utility rights-of-ways and roadsides). The HQT is intended to evaluate monarch habitat on those lands.

Participants in the Monarch Exchange will be subject to certain limitations and required to implement best management practices depending on conditions present at the site. For example, participants will not be allowed to apply insecticides on enrolled acreage; apply herbicides except to improve habitat for monarchs; or burn, mow or hay during times monarchs may be present. Improper management of a site will impact the ability of a site to perform at the capacity estimated by the HQT. Recommendations for management actions are provided in the Monarch HQT User's Guide.

Geographic Scope

The HQT is applicable in both the eastern and western subpopulations, but it is important to note that the methods are based on a clearer understanding of breeding biology for the eastern subpopulation, and that ongoing testing and data collection in the Western subpopulation may inform future versions of the HQT. Variations of the scoring model are developed for unique regions in the U.S. Regional boundaries are based in part on boundaries used in recent studies by

Oberhauser (2016) and Flockhart (2017) (Figure 1). Suitability levels of indicators and weighting of indicators in the combined model are modified for regional variations. A unique scoring model has been developed for the North Central region, South Central region, and for the western subpopulation. An additional scoring model for the Northeastern and Southeastern U.S. will also be developed.

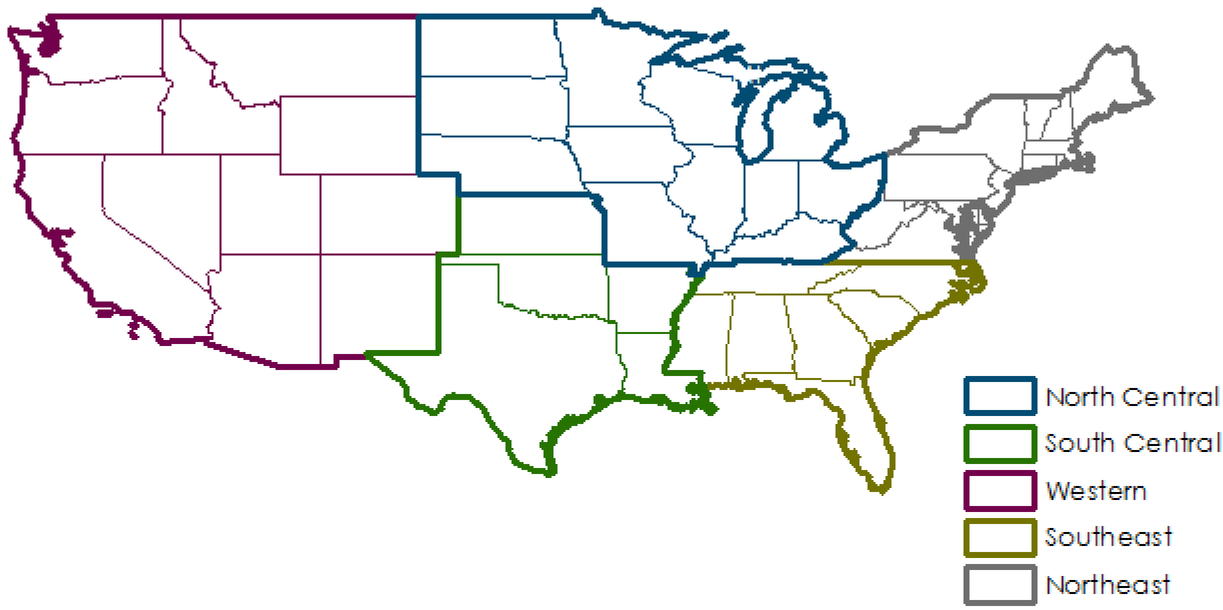

Figure 1. The geographic scope of the Monarch HQT includes all breeding and migrating habitats in the continental U.S. Regional variations of the Monarch HQT have been developed for the regions outlined.

The HQT is expected to eventually cover the entire range of monarch butterfly habitat in the United States, including breeding/migrating and overwintering habitat types in both the eastern and western populations, although at this point, more data exist that allow us to quantify habitat needs for the eastern population during the breeding portion of its annual cycle.

Intended Users

Individuals applying the HQT are expected to have field work experience and at least some background or training in botany and monarch butterfly biology. NRCS staff may also use the HQT in conjunction with the NRCS Monarch Butterfly Habitat Development Project and other Farm Bill programs such as Environmental Quality Incentives Program (EQIP), Conservation Stewardship Program (CSP), or Wetlands Reserve Easement (WRE) to select project sites or estimate project outcomes. Organizations such as Pheasants Forever and agencies such as Soil and Water Conservation Districts may utilize the HQT to design monarch habitat projects. The MCSP Integrated Monitoring Project could utilize the HQT for users that are unable to carry out the entire monitoring framework, such as citizen scientists.

Intended Uses

The HQT is applicable to any breeding or migratory monarch habitat in the United States, but was specifically designed for use in agricultural areas and within corridors such as rights-of-way.

Agriculture

Agricultural areas offer the largest opportunity for restoring monarch breeding habitat. Examples of land areas that may be enrolled in this effort include fallow crop lands, marginally productive land that is currently being farmed, grazing lands, fencerows, and areas between fields.

Roadsides & Rights-of-Way

Roadsides and Rights-of-Way, while perhaps not large contributors to monarch populations in the past relative to other habitat types, have become more significant due to loss of habitat in the rest of the agricultural landscape (Flockhart et al. 2015, Kasten et al. 2016). Entities managing these habitat types have the capabilities and resources to leverage an HQT and increase habitat availability at a large scale. For example, the Iowa DOT has an Integrated Roadside Vegetation Management program that supports native plant restoration on roadsides, and the HQT may serve as a tool to help restore, enhance and manage Iowa roadsides specifically for monarchs.

Other Habitat Types

Gardens and public-agency-managed natural areas are not specific foci of the HQT. However, while circumstances present in those habitat types may not have been envisioned by this ecological model, conclusions drawn from this model should be generally applicable in these habitat types.

Exclusions

Forested areas (forested swamps, riparian forested areas, or forested uplands), bodies of open water, and other areas where management for monarch habitat is not prioritized should be excluded from assessment of habitat using the HQT. Land managers may use the Monarch HQT to inform the prioritization of potential monarch habitats on their property for management as monarch habitat or for other objectives.

Application Scale

Spatial Scale

The HQT should be applied at the scale of individual parcels, termed ‘assessment areas’ in the HQT. For large projects, the site should be divided into ecological sites or similar units based on landscape attributes, soils, vegetation, and management actions to provide meaningful interpretation of model outputs. Each assessment area is evaluated separately, resulting in an index value for habitat suitability (i.e., a score between 0 – 100%) and number of functional acres (i.e., the size of the site measured in acres multiplied by the habitat suitability score, expressed as a percentage). Results from the evaluation of each analysis area can be combined to inform credit awards for the entire site. However, each assessment area should be considered separately when evaluating management alternatives and assessing outcomes from restoration and enhancement actions.

Temporal Considerations

Monarchs require milkweed and nectar resources throughout the time they are present in a region. Ideally, data would be collected periodically throughout the year. In order to provide an efficient means of habitat evaluation, we allow for a single site visit to collect data for sites located in the North Central region and Western Subpopulation regions. For sites in the South Central region, two field visits are required because monarchs utilize habitats differently during the spring and fall in this region. Field data should preferably be collected for the HQT during peak monarch site use, but it is important to note that the timing of peak use can vary from year to year. For more information on when monarchs are present near the area of interest, refer to Journey North's citizen-science observational data available at https://www.learner.org/jnorth. These data indicate first sightings of monarchs; peak monarch site use will take place some weeks after these first sightings.

Permissible windows for field data collection are provided in Table 1. Where two sampling windows are provided but only one visit is required (e.g., North Central region), the suitability indices used to assess habitat suitability may vary based on the season of the site visit. While sampling should always be conducted during the permissible window, the exact timing of the field data collection should take into account local conditions—ideally, sampling would take place at peak milkweed density during the sampling window.

Table 1. Permissible Sampling Windows

REGION	SAMPLING WINDOWS
North Central	▪ May 15 – July 1 (Mid-Season: earlier weeks in south part of region, later in north) ▪ July 1 – September 15 (Late Season)
South Central	▪ March 15 – May 15 (Early Season) ▪ September 1 – October 15 (Late Season)
Western	▪ May 20 – October 1 (early and late periods of this window will not be appropriate in the northern part of the region)
Northeast	▪ TBD
Southeast	▪ TBD

Results from the HQT assessment reflect the expected capacity of a site to produce and support monarchs over a single year. We assume that intra-annual variability is consistent among all sites or time periods which are being compared, and that diversity of milkweeds and nectar sources is positively correlated with resource availability throughout the year and during atypical weather, such as drought, mitigating the risk of overestimating the value of a site. The scoring model output should not be interpreted as a point-in-time estimate of monarch production.

When evaluating a restoration or enhancement project, an HQT assessment should be conducted to establish a benchmark reflecting pre-project conditions and again after the project in order to assess outcomes.

INDICATOR FRAMEWORK

Indicators—habitat characteristics which are determinant of monarch habitat suitability—are organized within an adaptable framework to facilitate adaptive management of the HQT, as described below:

- **Site Capacity:** Site capacity reflects the relative suitability of a site for monarchs based on observed and expected relationships between key habitat characteristics and immature and adult monarch densities.
- **Threats:** Threats impact site capacity by reducing the survivorship of monarchs produced and supported by the site. Within the scope of the HQT, the primary threat to monarchs is risk of pesticide exposure. Other threats to monarchs, such as incompatible mowing or haying, are not included in the HQT because those actions are prohibited for projects enrolled in an Exchange.
- **Opportunity:** Opportunity describes the ability of a site to perform at its expected site capacity based on local-scale and landscape-scale factors that influence the site. Given that monarchs are considered strong dispersers, and little is known about the effects of the surrounding landscape on monarch habitat, no opportunity indicators are currently included in the HQT.
- **Conservation Priority:** Conservation priority is based on the relative contribution of a region to overwintering colony populations, and is informed for the eastern subpopulation by Oberhauser et al. (2016), where prioritization of regions is focused on boosting carrying capacity that will result in increased winter population levels. Prioritization models for the western subpopulation are being investigated.

SITE CAPACITY

MILKWEED AVAILABILITY

Monarchs rely solely on milkweeds (plants in the genus *Asclepias* and a few closely related genera) as larval food sources. Therefore, milkweed is an essential feature of monarch habitat. Monarchs and other pollinators also utilize milkweed as a nectar source while in bloom. There are over 100 species of milkweed in North America, although monarch conservation organizations have prioritized species for each region of the U.S. (highlighted on the Monarch Joint Venture's Milkweed Information Sheet, MJV 2016a).

Density of Native Milkweed Stems

Because milkweed is necessary for monarch reproduction, it is logical to assume that higher densities of milkweed would lead to greater production of monarchs. However, few studies have measured monarch production based on consistent measures of milkweed density. Milkweed data from the Monarch Larva Monitoring Project (MLMP 2016), for example, are typically reported on a per-site basis, but not a per area basis. Agricultural studies of milkweed density often use estimates of the number of square meters “infested” per hectare, but do not report the actual densities of milkweed stems. To our knowledge, only one study in one region (the upper Midwestern U.S., Kasten et al. 2016) has done a comprehensive survey of milkweed stem density and related that to monarch density. Over 1,000 randomly selected 50-meter stretches of roadside in MN, SD, IA, WI, and IL were evaluated. In a model predicting the density of immature monarchs on a per area basis, milkweed density was the most significant positive predictor, but the data suggest that monarch production (monarch egg and larvae per square meter) in roadsides is maximized at about 0.6 milkweeds per square meter (Kasten et al. 2016).

Although it seems that higher densities may be beneficial for monarch production, it is rare that areas such as fallow fields and native prairie in the Upper Midwest have milkweed densities above 0.15 stems per square meter. Accounting for the assumptions made in the analysis, a reasonable estimate of the density at which the marginal returns for monarchs of additional milkweed become very low is approximately 0.5 stems per square meter or 2,000 stems per acre (Figure 2). Densities above 0.5 stems per square meter may be undesirable in most natural contexts, and rewarding landowners for greater densities may provide a perverse incentive to manipulate milkweed (and possibly monarch) density beyond sustainable ecological thresholds and at the cost of other ecosystem services provided by a diverse plant community.

Non-native milkweed species are not counted towards estimates of milkweed density.

In the North Central region, milkweed must be present on site to generate functional acres. Sites where milkweed is not present or is not expected to be present after creation or restoration of the habitat on the site should not be evaluated with the HQT.

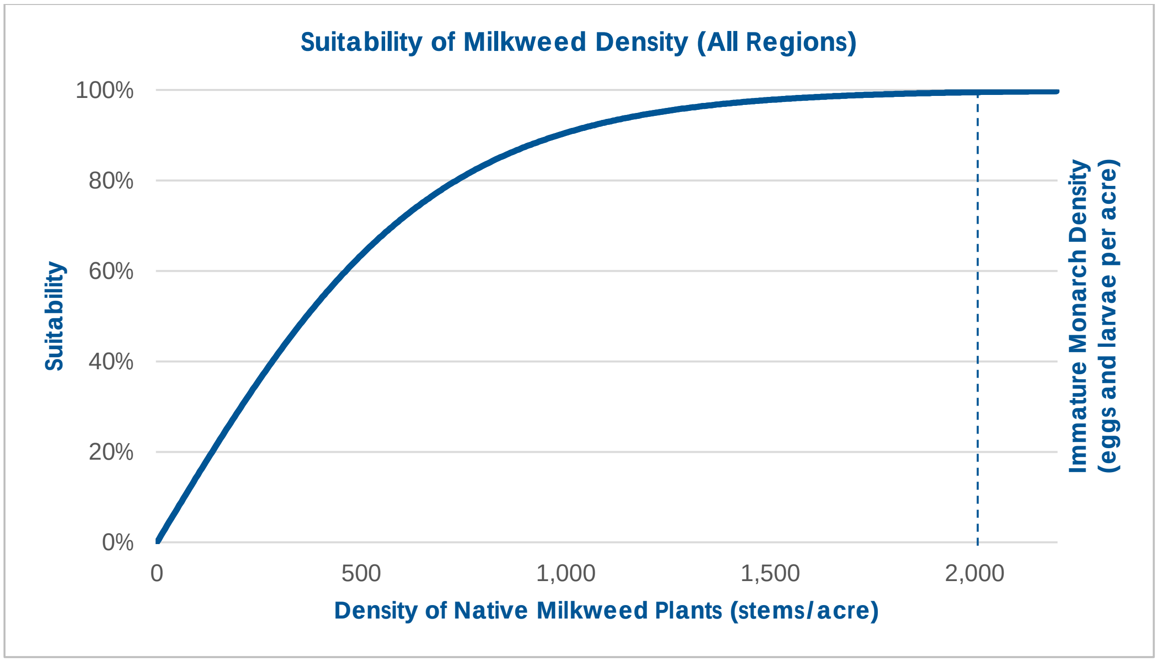

Figure 2. Milkweed Density Suitability Index (SI) for all regions of breeding/migratory habitat in the U.S. This SI is derived based on expert opinion of monarch biologists and a comprehensive survey of milkweed stem density and monarch density, which evaluated over 1,000 randomly selected 50-meter stretches of roadside in MN, SD, IA, WI, and IL (Kasten et al. 2016). The suitability of milkweed density is related to immature monarch densities (eggs and larvae per acre).

The Milkweed Density SI is given by Equation 1.

Equation 1

$$Milkweed\ Density\ SI = 1 - \frac{2}{1 + exp(6 * \frac{x}{2000})}$$

Where:

x: density of native milkweed stems expressed in stems per acre

Diversity of Native Milkweeds

Diversity promotes resilience in ecosystems. Each species is adapted to specific conditions related to soil, temperature, shade, water availability, disturbance, slope, and other factors. Sites with high diversity are less susceptible to losses of milkweed during weather events such as drought and other perturbations. Additionally, different milkweed species are more attractive to monarchs at different times of the year and species with later blooming periods tend to be available later in the year after species with earlier blooming periods have senesced. For example, *A. verticillata* has indeterminate growth, and thus more fresh leaf tissue at the end of the season, when other species are senescing (Karen Oberhauser, personal observations). *A. asperula* is generally available early in the year and *A. latifolia* is generally available late in the year (Kristen Baum, personal observations).

Milkweeds are assumed to be locally adapted and will be better host plants if growing in conditions similar to those in their evolutionary history. Only native milkweeds should be included in estimates of milkweed diversity. Monarch Planting Lists developed by the NRCS are available to determine milkweed species that are native and common to a particular region (USDA NRCS 2016c). It should be noted that not all regions or sites are suitable for a high diversity of milkweed species. Consult your local seed provider for information about milkweed species suitable for any particular site (find milkweed seed providers at www.xerces.org/milkweed-seed-finder).

Milkweed diversity is expressed as number of effective species, or True Diversity, as calculated using Simpson's Index. Simpson's Index incorporates measures of species richness and evenness, which provides more information about milkweed diversity than species richness alone (see *Data Transformation* section below for application of Simpson's Index). Optimal values shown on Figure 3 are derived from best professional judgement.

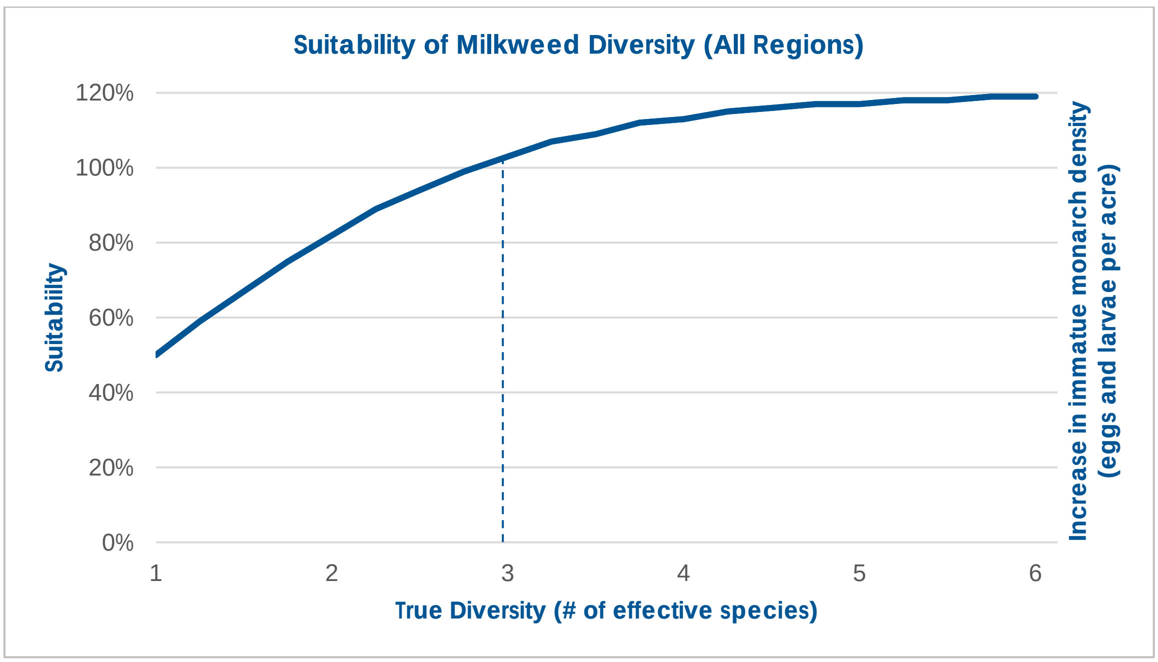

Figure 3. Milkweed Diversity Suitability Index (SI) for all breeding/migratory habitats in the U.S. The SI is derived based on expert opinion of monarch biologists. Simpson's Index is used to estimate True Diversity (D), which is translated to suitability. The suitability of milkweed diversity is related to expected increases in immature monarch densities (eggs and larvae per acre) as diversity increases. The maximum suitability of 120% provides a 'bonus' for highly diverse sites without penalizing sites with reasonably good diversity.

The Milkweed Diversity SI is given by Equation 2.

Equation 2

$$Milkweed\ Diversity\ SI = 1.2 - \frac{1.4}{1 + exp(\ D - 1\ )}$$

Where:

D: number of effective species

Data Transformation

We use Simpson's Index to estimate the number of 'effective species' (D), which is a measure of diversity that includes both evenness and richness (Equation 3).

Equation 3

$$D = \frac{1}{\sum_i p_i^2}$$

Where:

p: proportional abundance of species *i*

The intent of this indicator is to differentiate sites commonly assessed by the HQT based on milkweed diversity. While higher species richness may be desirable, values above the optimal value are relatively rare in fallow fields and natural areas. A maximum suitability of 120% provides a 'bonus' for highly diverse sites without penalizing sites with reasonably good diversity.

Presence of Non-Native Milkweed

There is some evidence that a non-native milkweed in the southern U.S., *A. curassavica*, may facilitate the build-up of a key monarch parasite, *Ophryocystis elektroschirra* (OE), because it is available for multiple generations (Satterfield et al. 2015). It may also affect monarch migratory behavior by being available during times that native milkweeds are not (MJV 2016b). Where *A. curassavica* is present on the site, it should be managed by cutting it back in the winter and fall months in the southern U.S. and California (excluding southern Florida). Data are not available to estimate an effect on monarch production due to presence or abundance of *A. curassavica*, so we have chosen not to discount the value of a site due to its presence, but rather to simply not include it in the assessment of milkweed density or diversity.

Combined Milkweed Suitability Index

The suitability scores for milkweed density and milkweed diversity are weighted and combined to calculate overall milkweed suitability according to Equation 4.

Equation 4

$$Milkweed\ SI = W_{Density} * \text{Density SI} + W_{Diversity} * \text{Diversity SI}$$

Weight for the Density SI and Diversity SI are based on the expectation that high diversity will increase monarch production by approximately 20%, which is based on expert opinion. Weighting for these two SIs is the same for all geographic regions. Weights are provided in Table 2.

Table 2. Weights for the Combined Milkweed Suitability Index by Region

REGION	DENSITY ($W_{DENSITY}$)	DIVERSITY ($W_{DIVERSITY}$)
North Central	80%	20%
South Central	80%	20%
Western	80%	20%
Northeast	TBD	TBD
Southeast	TBD	TBD

NECTAR SOURCE AVAILABILITY

Unlike larvae that rely only on milkweed to survive, adult monarchs use diverse nectar sources for food. Nectar plants are a key component to prime habitat for monarchs and other pollinators.

Spring blooming nectar plants (blooming approximately March 20—June 1) fuel the monarch migration northward from Mexico and inland from the California coast. Without abundant nectar sources through the migratory corridors, monarchs are probably less likely to survive and may not be able to reproduce successfully. Summer blooming nectar sources (blooming approximately June 2—August 15) throughout the breeding range are vital to sustain a healthy breeding population. Fall blooming nectar plants (blooming approximately August 16—October 30) are equally important; monarchs rely on abundant nectar sources in the fall to store enough energy not only to survive the long journey to their overwintering sites, but also to survive winter with very minimal nectar availability.

While non-native species can be used for nectar, native nectar plants are often more beneficial to an ecosystem. Native plants are well suited for the climatic conditions of an area and are responsible for important ecosystem functions, such as erosion control and filtration. Only native nectar plants are included in the assessment of nectar source availability. A site without native nectar plants will receive a score of zero for foraging habitat.

Blooming Forb Frequency

Adult monarchs need continuously available nectar sources for migrating and breeding. Because migrating monarchs need to convert and store lipids obtained from nectar sources in large enough quantities to survive the winter, late-season nectar sources from the Great Plains southward are critical for wintering survival (Brower et al. 2006). While monarchs are observed foraging during the winter in Mexico, there are not enough flowers in and near the overwintering forests to accommodate the millions of monarchs that are there. Overwintering monarchs must survive during the winter on the lipid reserves that they built up as larvae and as adults during the fall migration (Alonso-Mejia et al. 1997).

Nectar source availability is assessed by measuring the frequency of blooming forbs in nested plots, where frequency is defined as the proportion of possible plots within an assessment area occupied by blooming forbs. Suitability of the assessment area is given by the average index value for all subplot areas sampled (0.25 m^2, 0.5 m^2, and 1 m^2).

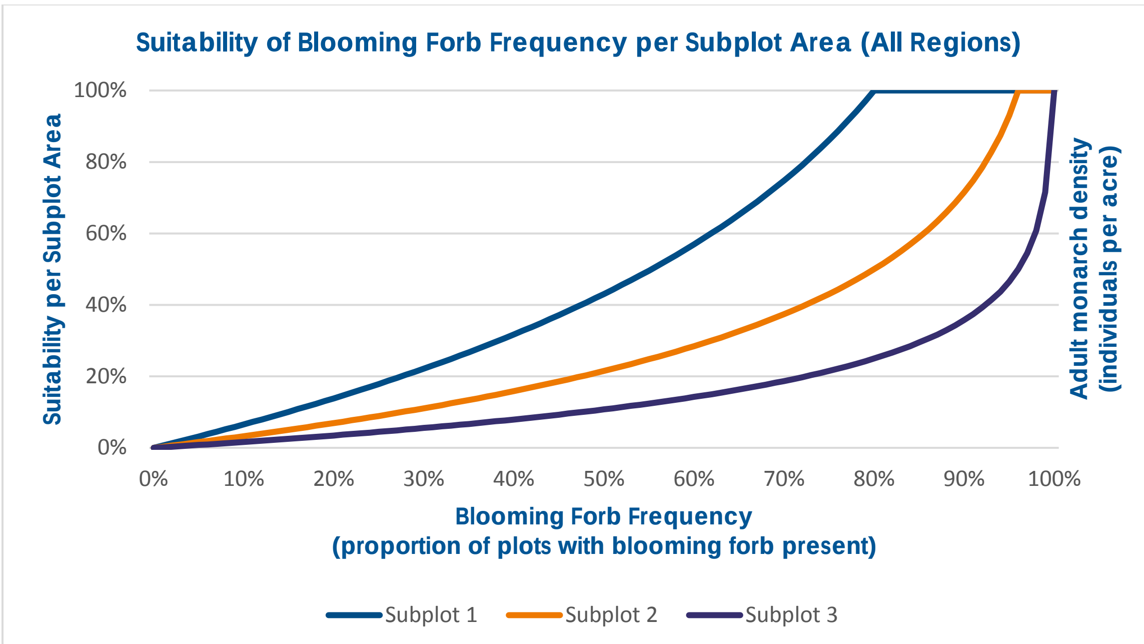

Figure 4. Blooming Forb Frequency SI for each subplot area for all breeding/migratory habitats in the U.S. The SI is derived based on expert opinion of monarch biologists. Frequency data are collected in three subplot areas (0.25 m^2, 0.5 m^2, and 1 m^2). Data are log-transformed to approximate density from frequency. The SI for each subplot area is averaged to calculate the SI for the assessment area. The suitability of blooming forb frequency is expected to be related to the density of adult monarchs (individuals per acre) and is based on expert opinion.

The Blooming Forb Frequency SI is given by Equation 5, assuming data are collected from three subplot areas.

Equation 5

$$Blooming\ Forb\ Frequency\ SI = \frac{1}{3}\sum_{i=1}^{3} 0.155 * \frac{-\ln(1-f_i)}{a_i}$$

Where:

f_i: frequency of subplot area *i* expressed as a proportion

a_i: area of subplot area *i*

The constant 0.155 is a scaling factor derived from the assumption that approximately 6.4 blooming forbs per m^2 represents fully-functioning habitat, which is based on expert opinion of monarch biologists (0.155 = 1/6.4). This density corresponds to the density of blooming forbs when the frequency of subplot 1 (0.25 m^2) is 80%. Where blooming forb density is calculated to be greater than 6.4 (i.e., the SI would be greater than 100%), the SI value assigned is 100%.

Data Transformation

Frequency is a rapid, objective, relatively simple method for collecting data on blooming forb availability, and it has lower sensitivity to periodic fluctuations than similar methods of estimating forb abundance (e.g., canopy cover). Measures of frequency reflect both density and dispersion. The availability of nectar sources is probably best approximated by density as opposed to frequency. The relationship of frequency to density is curvilinear—changes in frequency at different frequency values do not reflect the same magnitude of changes in density. The relationship of frequency to density, assuming random dispersion of individuals in the sample, is given by Equation 6 (Morrison 1995, Hyder 1965).

Equation 6

$$f = 1 - \exp(-d * a)$$

Where:

f: frequency of blooming forbs expressed as a proportion

d: density, or number of blooming forbs per unit area

a: area of the subplot

The suitability index for each plot area (Equation 5) is derived using this relationship between frequency and density, as provided by Equation 6. In other words, this data transformation is implicit in the suitability index; no transformation is required to evaluate the suitability of frequency data using the suitability index. While this transformation is imperfect, it allows for a more linear interpretation of frequency data on monarch habitat suitability and partially corrects for the plot size dependence of frequency data. This allows the HQT to use all three plot sizes in the calculation of habitat suitability.

During ongoing monitoring of the site, managers should assess changes in frequency values per species in combination with field observations to inform adaptive management decisions and should not rely solely on changes in the suitability index as calculated using the HQT.

Blooming Forb Richness

The number of unique forb species currently in bloom is recorded for the entire assessment area. Because monarchs require nectar sources throughout the time they are present on the site, optimal forb richness values are provided for multiple sampling windows (see Table 3). Sampling during a single window is sufficient for evaluation of habitat in the North Central region and Western Subpopulation regions, however optimal values for different times of the year provide important information to land managers to allow them to maximize the suitability of their site for monarchs by establishing a diverse stand of forbs that provide a source of nectar for monarchs throughout the year. In the South Central region, two site visits are required, one during each sampling window (early season and late season).

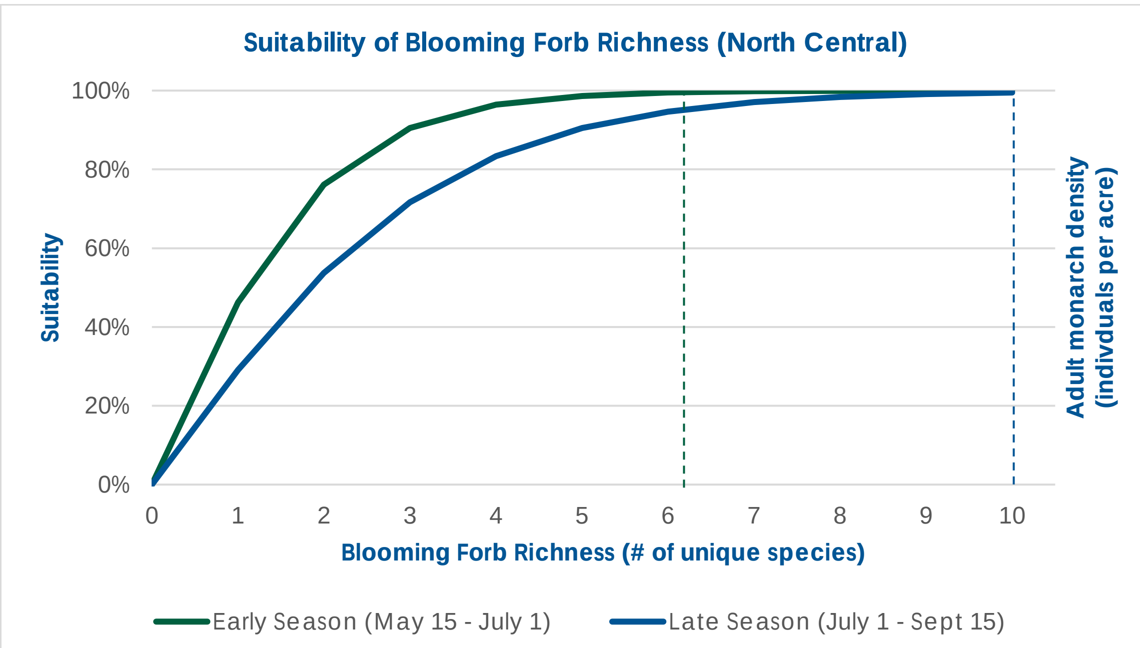

Figure 5. Blooming Forb Richness Suitability Index (SI) for the North Central region. The SI is derived based on expert opinion of monarch biologists. The suitability of blooming forb richness is expected to be related to adult monarch density (individuals per acre) and is based on expert opinion.

The Blooming Forb Richness SI is given by Equation 7.

Equation 7

$$Blooming\ Forb\ Richness\ SI = 1 - \frac{2}{1 + \exp(6 * \frac{y}{max})}$$

Where:

y: number of unique blooming forbs in the assessment area

max: number of blooming forbs characteristic of fully-functioning habitat.

Table 3 provides the number of blooming forbs characteristic of fully-functioning habitat for each region and season of field data collection. If field data are collected during multiple sampling windows the maximum overall score (including all parameters measured by the HQT) for the site should be used for the purposed of the Monarch Exchange.

Table 3. Optimal blooming forb richnesses by region and season

REGION	EARLY SEASON	MID-SEASON	LATE SEASON
North Central	n/a	(May 15 – July 1) **6**	(July 1 – Sept 15) **10**
South Central	(Mar 15 – May 15) **10**	n/a	(Aug 15 – Oct 15) **10**
Western	n/a	(May 20 – Oct 1) **TBD**	n/a
Northeast	TBD	TBD	TBD
Southeast	TBD	TBD	TBD

Preferred Forb Species

One source suggests that monarchs prefer plants with relatively flat surfaces or long multi-flowering inflorescences where the nectar is easily accessed (USDA - NRCS 2016c), but there is limited research on this topic. Monarch nectar plant guides developed by the NRCS and Xerces Society are available to determine nectar source preference by species for regions in the U.S. (USDA- NRCS 2016c; available at www.nrcs.usda.gov/monarchs and www.xerces.org/monarch-nectar-plants). Eventually, the HQT may include a preferred list of species, and beginning with the USDA documents would be reasonable. However, at this time the HQT does not limit estimates of nectar source availability to forbs currently listed as preferred in those documents.

Combined Nectar Source Suitability Index

The suitability scores for forb cover and richness are weighted and combined to calculate combined nectar source suitability according to Equation 8.

Equation 8

$$Nectar\ SI = W_{Frequency} * \text{Frequency SI} + W_{Richness} * \text{Richness SI}$$

Nectar SI weights for each region are provided in Table 4. Weights are based on expert opinion of the relative importance of frequency and richness of blooming preferred forbs to monarch habitat suitability.

Table 4. Weights for the Combined Nectar Suitability Index by Region

REGION	FREQUENCY ($W_{FREQUENCY}$)	RICHNESS ($W_{RICHNESS}$)
North Central	60%	40%
South Central	60%	40%
Western	60%	40%
Northeast	TBD	TBD
Southeast	TBD	TBD

SITE SIZE

Total monarch production is assumed to increase linearly with site size, all other factors being equal.

Monarch butterflies are excellent dispersers and utilize habitats with milkweeds regardless of the size of the site. Small butterfly gardens and large natural areas may differ in many respects, but both types of sites can contribute to monarch reproduction. Larger sites typically experience less disturbance and more diverse plant and animal communities than smaller sites. While small sites may be equally valuable on a per area basis to large sites, the creation and support for larger sites will be necessary to replace the many milkweed stems that have been lost to conventional agriculture and land use changes across North America.

Based on Monarch Larva Monitoring Project data, smaller sites (i.e., those with fewer milkweed plants) tended to have more eggs per plant, yet lower larval survival than larger sites (Stenoien et al. 2015, Nail et al. 2015). This trade-off between egg density and survival likely equalizes overall production on a per area basis, which is why the value of a site increases linearly based on area.

Site size, measured in acres, is used to calculate functional acres available on a site. Completely forested areas or bodies of water do not contribute towards site size.

THREATS

Herbicides and insecticides are potentially problematic for restoration efforts of milkweeds and monarch butterflies. Full suitability cannot be achieved when insecticides are used on a site and it may be difficult to quantify the loss of monarchs resultant from insecticide use, thus insecticide use is prohibited on habitat enrolled in the Exchange. Herbicide use in and adjacent to monarch habitat should be avoided, or closely controlled to achieve full suitability (although herbicides can be effectively used during the restoration process or to control weedy species that may compete with milkweed and nectar species). The biggest risk of pesticides to milkweeds and monarch is expected to be due to transport from adjacent lands during and after pesticide application. Spot application of herbicides and the use of Integrated Pest Management plans can allow for control of invasive species while limiting impacts to monarchs. An analysis of potential sites for establishing new monarch habitat indicated that approximately 80% of rural roadsides and 40% of non-crop areas in Story County, IA are within 125 feet of fields in conventional agricultural (Tyler Grant pers. comm.). Excluding these potential habitats from conservation efforts would very likely preclude achievement of the conservation targets for monarch habitat necessary to reduce quasi-extinction risk.

RISK OF PESTICIDE EXPOSURE

Habitats that are adjacent to conventional agriculture are likely to be impacted by drift, runoff or dustoff of both herbicides and insecticides, depending on application procedures and environmental conditions at the time of spraying (Felsot et al. 2010). The presence of windbreaks, such as hedgerows, at the boundary between crop and non-target areas can decrease aerial pesticide drift into non-target areas (Felsot et al. 2010, USDA 2014). Hedgerows installed for the purpose of protecting habitat from pesticides should not contain milkweed or other flowering plants. A buffer zone of 6 meters appears to be sufficient if spraying is done under appropriate conditions, but 10% mortality of non-target insects at distances of up to 24 meters have been recorded when spraying was carried out under windy conditions (Felsot et al. 2010).

We adopt the specifications from the NRCS WHEG (USDA NRCS 2016a), which reduces habitat suitability by 70% for any areas within 38.1 meters (125 feet) of areas treated with pesticides. Where a hedgerow is present, the reduction in habitat suitability will be 40%. To qualify, hedgerows must conform to recommendations established by the NRCS (USDA 2014, Appendix B). Additional mitigating factors may be considered for future versions of the HQT. Because it can be difficult to verify pesticide use on neighboring cropland, any areas of conventional (e.g., non-organic) cropland will be considered as areas where pesticides are applied, unless clearly demonstrated otherwise. The Pesticide Risk SI is calculated according to Equation 9.

Equation 9

$$Pesticide\ Risk\ SI = 1 - \frac{(0.7 * A_{High} + 0.4 * A_{Low})}{Assessment\ Area}$$

Where:

A_{High}: Area within 38.1 meters (125 feet) of conventional agriculture, unprotected

A_{Low}: Area within 38.1 meters (125 feet) of conventional agriculture protected by a hedgerow

Need for Additional Information

The positive valuation of monarch habitat at risk of drift, runoff and dustoff of agricultural chemicals by nearby production agriculture, even when protected by hedgerows or other mitigating actions, risks the creation of populations sinks for monarchs if the habitat receives credits through the Exchange. While there have been significant efforts to better understand and quantify the effects of pesticides on monarch populations, much is still unknown. Given the potential importance of habitats near the margins of agricultural fields to the successful conservation of monarch butterflies, it is our opinion that the benefits to monarch populations of the additional habitat that can be created in these areas outweigh the potential risks to monarchs due to insecticide exposure, and that the relative benefits are reasonably estimated by the Pesticide Risk SI equation (Equation 9).

The risk to monarchs from pesticides, options for mitigating the risk to monarchs from pesticides, and site characteristics that can distinguish habitat as a population sink will be investigated through adaptive management of the HQT. It is important to note that each local Exchange may enact rules concerning the allowable proximity to conventional agriculture of monarch habitats enrolled in that program. The Exchange may, for instance, require participants to limit their own application of pesticides on agriculture fields near enrolled habitat. However, it is not possible to require all neighboring landowners to also limit their own application of pesticides. The value of habitats near a neighbor's agricultural fields will be a function of the proximity to their neighbor's field and the presence of mitigating factors such as hedgerows.

COMBINED THREAT SI

The Threat SI is equal to the Pesticide Risk SI, as shown in Equation 10.

Equation 10

$$Threat\ SI = Pesticide\ Risk\ SI$$

OPPORTUNITY

The area surrounding a monarch habitat is likely to influence monarch use of a site and survival. Land use changes have caused natural areas to be fragmented into smaller, more isolated parcels of land disbursed throughout an ecosystem. The degree to which a patch is isolated from other milkweed habitat could affect monarch densities (both adults and immature stages) in several ways. First, densities could be higher in isolated patches, if monarchs find the patches as they are searching a wide area without appropriate habitat, and/or remain in isolated patches for longer, continuing to lay eggs. Second, monarch densities could be lower in isolated patches, if monarchs leave an area sooner when they do not encounter appropriate habitat after some amount of searching time. In this case, monarch breeding habitats in close proximity to each other may allow monarchs to find suitable habitat without traveling long distances. Third, landscape-level features surrounding a habitat patch may not affect monarch density within the patch, if monarchs move across the landscape in a way that is unaffected by the appropriateness of the habitat through which they are flying.

At this point, we assume that habitat patches surrounded by areas with natural vegetation are more beneficial to monarchs than surrounding land that has been altered by development or agriculture. Natural vegetation surrounding any wildlife habitat reduces the risk of danger by human contact. Milkweed habitat mixed within human inhabited areas is important for monarch populations, but it may increase the risk of injury or death to monarchs by vehicles or other anthropogenic risks, such as insecticide applications.

Until the effects of the surrounding landscape on monarch reproduction and survival are better understood, the HQT will focus on the characteristics of the site itself, and not the surrounding area. However, sites immediately adjacent to areas that are sprayed with insecticides will probably not achieve full suitability due to the risk of pesticide exposure (see *Threats*).

CONSERVATION PRIORITY

Conservation priority is based on the relative contribution of a region to overwintering colony populations, and is informed for the eastern subpopulation by Oberhauser et al. (2016) where prioritization of regions is focused on boosting carrying capacity that will result in increased winter population levels. Prioritization models for the western subpopulation are being investigated.

REGIONAL CONSERVATION PRIORITY

Within the central portion of the US, the areas around the Corn Belt and around the central flyway in Texas appear to be most critical to monarch conservation (Flockhart et al. 2015, Oberhauser et al. 2016). The Corn Belt was the source of most monarchs that migrated to Mexico, at least before the widespread use of herbicide-tolerant row crops (Flockhart et al. 2017, Wassenaar and Hobson 1998, Chip Taylor, personal communication), and more recent data from the Monarch Larva Monitoring Project suggest that this is still the case (Stenoien et al. 2015). Texas is important because (1) it hosts monarchs in the spring when monarchs are recolonizing the eastern U.S. and during the fall when monarchs are migrating to Mexico, and (2) most of the monarchs in the entire eastern migratory population pass through this area on their way to and from Mexico.

While monarchs are also produced in the eastern U.S., a smaller percentage of these monarchs contribute to the overwintering population. The limited data available indicate that the eastern portion of the monarchs' eastern range is less productive in terms of contributions to the overwintering population as the central portion of the US. (Wassenaar and Hobson 1998, Stenoien et al. 2015, Chip Taylor, personal communication).

McCoshum et al. (2016) modeled the distribution of several known monarch predators. Their findings suggest that predator pressure could be greatest in the southeastern region of the U.S., based on the number of predator species predicted to be present. Future models could prioritize regions based on the likelihood of monarch survival, but to date the relationship between the number of predator species present and survival is unknown.

Yang et al. (2015) have analyzed the natal origins of the western overwintering monarch population. Their data do not justify prioritization of one portion of the western range over others. USFWS and Xerces have developed a draft western monarch habitat suitability model (available at https://catalog.data.gov/dataset/usfws-xerces-society-western-milkweed-and-monarch-breeding-habitat-suitability-models), which may provide a basis for prioritization within areas of the West. These models are currently being investigated.

Further study of natal origins of overwintering monarchs, migratory survival, and egg density averages per region could improve the prioritization of regions for conservation of monarchs.

The conservation priority suitability index for each region is provided in Table 5. These values are based on expert opinion of monarch biologists and Oberhauser et al. (2016).

Table 5. Conservation Priority Values for each region

REGION	CONSERVATION PRIORITY
North Central	100%
South Central	100%
Western	100%
Northeast	85%
Southeast	85%

AGGREGATION METHOD

HSIs are calculated for both breeding and foraging habitat to allow for land managers to identify deficiencies in a site and prioritize restoration and enhancement actions. The general form of the HSI is:

Equation 11

$$\text{HSI} = \text{Site Capacity SI} * \text{Threat SI} * \text{Opportunity SI} * \text{Conservation Priority SI}$$

BREEDING HSI

Site capacity for the breeding HSI is equal to the Milkweed SI. The equation for the Breeding HSI is:

Equation 12

$$\text{HSI}_{Breeding} = \text{Milkweed SI} * \text{Threat SI} * \text{Opportunity SI} * \text{Conservation Priority SI}$$

Because there are no indicators for Opportunity at this time, a value of 1.0 should be used for the Opportunity SI.

FORAGING HSI

Site capacity for the Foraging HSI is equal to the Nectar Source SI. The equation for the Foraging HSI is:

Equation 13

$$\text{HSI}_{Foraging} = \text{Nectar Source SI} * \text{Threat SI} * \text{Opportunity SI} * \text{Conservation Priority SI}$$

Because there are no indicators for Opportunity at this time, a value of 1.0 should be used for the Opportunity SI.

COMBINED HSI

The Breeding and Foraging HSIs are combined to calculate a single HSI for the site using a weighted sum model. Weights are based on expert opinion of the relative importance of breeding and foraging habitat for monarchs.

Equation 14

$$\text{HSI} = W_B * (\text{HSI}_{Breeding}) + W_N * (\text{HSI}_{Foraging})$$

In the North Central region, the best available science indicates that breeding habitat is limiting (Pleasants and Oberhauser 2013); thus, breeding habitat suitability is weighted more heavily. In South Central region, less is known but variability in nectar sources due to weather patterns is likely a key driver of monarch population levels. Thus, breeding and foraging habitat are weighted evenly. Very little is known about the western subpopulation, and thus weights from the North Central region were used. Weights are provided in Table 6.

Table 6. Weights of Breeding and Foraging HSIs for Combined HSI

REGION	BREEDING (W_B)	FORAGING (W_N)
North Central	75%	25%
South Central	50%	50%
Western	75%	25%
Northeast	TBD	TBD
Southeast	TBD	TBD

FUNCTIONAL ACRES

The HSI is multiplied by site area in acres to calculate functional acres. Completely forested areas or bodies of water do not contribute towards site size.

Equation 15

$$\text{Functional Acres} = \text{HSI} * \text{Site Area (in acres)}$$

INTERPRETATION OF HSI & FUNCTIONAL ACRES

The scoring model produces an index of habitat suitability (HSI value) and number of functional acres for each assessment area. An overall HSI value is produced and individual HSI values are produced for breeding and foraging habitat. The outputs of the scoring model can be used to compare multiple sites or management alternatives, assess changes at a site through time, and track program-wide progress.

HABITAT SUITABILITY INDEX

The combined HSI provides a relative measure of a site's capacity to produce and sustain monarchs and contribute to winter populations. The HSI and the constituent indicators can be used to assess the current condition of a site, analyze alternative project designs based on hypothetical changes, and compare the suitability of a site at multiple points in time. Expected changes resulting from treatments or changes in management regime can be compared to identify the most beneficial alternatives. Incorporating an understanding of the cost of each alternative, the most cost-competitive actions can be selected, resulting in the maximization of benefits for monarchs per conservation dollar. The data collection needs of the HQT can also serve as a basis for developing ongoing monitoring programs.

FUNCTIONAL ACRES

Functional acres represent the total output of a site in terms of monarch production, site use, and contribution to overwintering colonies. Functional acres should be compared when evaluating multiple sites of different sizes. Functional acres can be aggregated across all sites participating in the Exchange to assess progress towards program goals. Changes to functional acres range-wide are expected to correlate with changes to winter population levels.

MONARCHS CONTRIBUTED TO WINTER POPULATIONS

In order to increase the interpretability of the scoring model outputs, we recommend transforming functional acres to number of monarchs potentially contributed to winter populations, referred to as 'monarch yield' using the following equation:

Equation 16

$$\text{Monarch Yield} = \text{Functional acres} * 70 \text{ monarchs per function acre}$$

The value of 70 is calculated by multiplying the number of monarchs likely to migrate to Mexico per milkweed plant (approximately 0.035, Nail et al 2015) by the number of milkweeds at optimal density in a functional acre (2,000 milkweeds per functional acre). We note that, in any comparison of HSI values or functional acres, the effect of this factor on the outcome is trivial. However, it increases the interpretability of the output.

LIMITATIONS

The HQT uses the best available science and expert knowledge currently available to provide guidance on how to increase monarch population numbers through habitat characteristics and through best management practices. However, there are still many unstudied aspects of how habitat affects aspects of monarch biology, including oviposition and survival. Additionally, the scientific and conservation communities are still determining how management and other site characteristics may affect monarchs specifically (and pollinators generally). As new information becomes available and more monitoring throughout the landscape occurs, the guidelines provided in this document may change to reflect this work. Important limitations of the HQT are discussed below:

1) The HQT does not assess all functions, values, and services that a site may support, such as the suitability of a site for other species. This tool may be augmented by tools that are intended for other species, such as pollinators. Where there may be a conflict between habitat requirements for different species, best professional judgement should be used.
2) The HQT has only limited ability to assess the potential of a site. While it can be used to assess different scenarios for any given site, it cannot tell the user if those scenarios are realistic given the biotic and abiotic characteristics of the site. Professional judgement should be used when assessing site potential and the expected outcomes of restoration projects.
3) The HQT and associated protocols are not intended to replace objective-based monitoring for the site. The aggregated outputs of the scoring models may mask proximity to ecological thresholds that may reduce resilience of the site. Objective-based monitoring plans are encouraged for all participating sites based on project-specific conditions and planned management actions.
4) Reasonable judgement should be used when interpreting the outputs of the HQT. The HQT does not measure all attributes of monarch habitat and demography. Management actions that adversely impact monarchs should be avoided. Considerations and recommendations for appropriate management of monarch habitats are provided in the Monarch HQT User's Guide.

QUALITY ASSURANCE

The HQT is based on a process-based (mechanistic) understanding of monarch ecology and habitat requirements. Process-based models identify *a priori* predictions of causal mechanisms that can be evaluated with independent data. This allows us to include indicators that are not well quantified, and to identify adaptive management needs. The hypotheses and relationships underlying each suitability index can be evaluated through long-term demographic study or controlled experiments, however we recognize that some of these relationships will be difficult to evaluate in practice.

Quality assurance for the Monarch HQT has been conducted through field testing, sensitivity analysis, and external review. The Monarch HQT is intended to be adaptively managed through time as additional science becomes available.

FIELD TESTING

Field testing of the Monarch HQT was conducted in the summer of 2016 to verify that the model outputs are reasonable and to test the field data collection protocols. Field testing locations are described in Table 7.

Table 7. Field Test Sites

REGION	SITE LOCATION	SITE DESCRIPTION	DATE
North Central	Blue Earth, MN	A farming operation. Habitat along roadsides and in a Conservation Reserve Program field was assessed.	▪ August 26th
North Central	Blue Earth, MN	A 35-acre plot within a USFWS prairie restoration project was assessed.	▪ August 25th
South Central	Travis County, TX	A large ranching operation in the central hills of Texas. Predominately oak/juniper savannah. Multiple ~10 acre sites were assessed.	▪ May 9th & 10th ▪ October 10th & 11th
Western	Sacramento County, CA	A farming and ranching operation in the Central Valley of California. A roadside and a restoration area were assessed.	▪ July 12th
Western	Yolo County, CA	A milkweed seed farm in the Central Valley of California. Multiple restoration areas were assessed.	▪ July 12th
Western	Yolo County, CA	Multiple monarch restoration projects were assessed along a community greenway.	▪ July 13th

SENSITIVITY ANALYSIS

Sensitivity analysis explores the effect of changes in input values on model output values (i.e., functional acres). Comparing the magnitude of these effects across all parameters helps identify parameters to which the Monarch HQT is most sensitive. This is especially important for the HQT to ensure that landowners and managers have the ability to influence the outcome of the HQT analysis.

The relative change in functional acre output per relative change in parameter value was evaluated for each parameter, holding all other parameters constant at the maximum score. Each parameter was incremented between 10% and 90% of its maximum value (i.e., +/- 40% from the mid-point value). For example, milkweed density, for which the maximum score is 2,000 stems/acre, was incremented between 200 stems/acre and 1,800 stems/acre. All other parameters were held at the maximum value. Results are presented in Figure 6 and Figure 7. Figure 8 and Figure 9 illustrate the results for site-capacity parameters only.

The sensitivity of the HQT to marginal changes in each parameter is represented by the slope of line associated with that parameter. For example, using the graphs below it is evident that the sensitivity of the HQT to acreage of habitat-at-risk of pesticide exposure is consistently high. The sensitivity to protecting habitat-at-risk with mitigating factors is also high, which should provide a positive incentive for landowners to mitigate the effects of pesticide exposure to monarch habitat.

For site-capacity parameters (i.e., milkweed abundance, milkweed diversity, blooming forb richness, blooming forb frequency), milkweed abundance is the parameter to which the HQT is most sensitive, especially at low values of milkweed abundance. This is a consequence of the high weight that milkweed abundance has in the HQT, and reflects the importance of milkweed abundance to monarchs, especially in the North Central region. In the South Central region, the HQT is more sensitive to blooming forb frequency, especially low and high values, than in the North Central region. This is expected, as the HQT weights nectar availability more heavily in the South Central region than in the North Central, due to its importance for migrating monarchs. Milkweed diversity and blooming forb richness are the least impactful on HQT outputs. The low sensitivity supports the decision to make evaluating those attributes, which requires the ability to identify forbs to species, optional for applying the HQT.

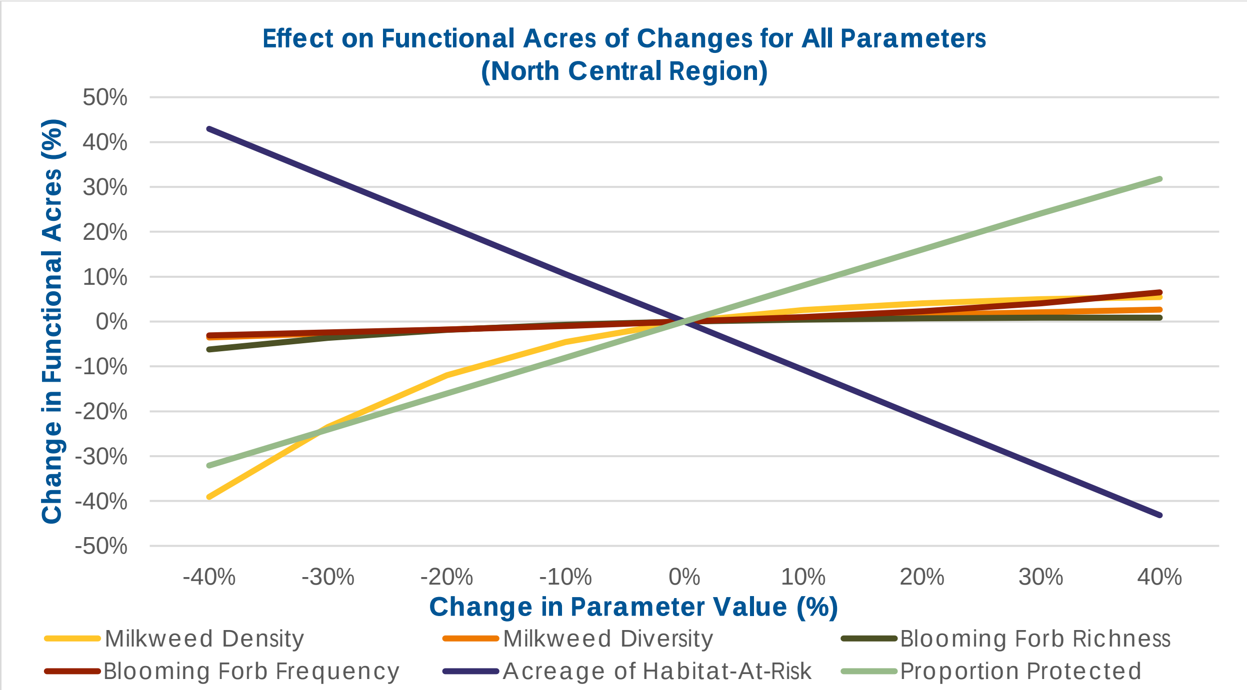

Figure 6. Sensitivity analysis for all parameters in the North Central region. The sensitivity of the HQT to each marginal change in parameter value is represented by the slope of the line associated with that parameter. The mid-point between the minimum and fully-functioning value of the parameter is represented here as a 0% change in parameter value.

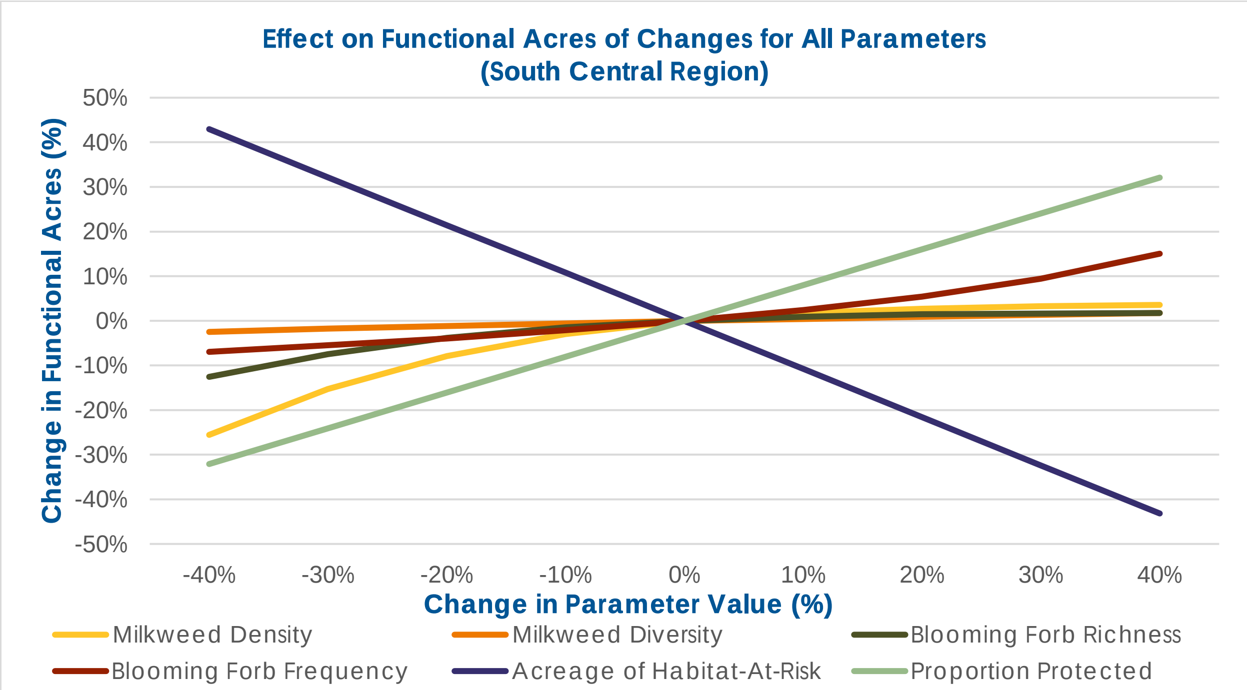

Figure 7. Sensitivity analysis for all parameters in the South Central region. The sensitivity of the HQT to each marginal change in parameter value is represented by the slope of the line associated with that parameter. The mid-point between the minimum and fully-functioning value of the parameter is represented here as a 0% change in parameter value.

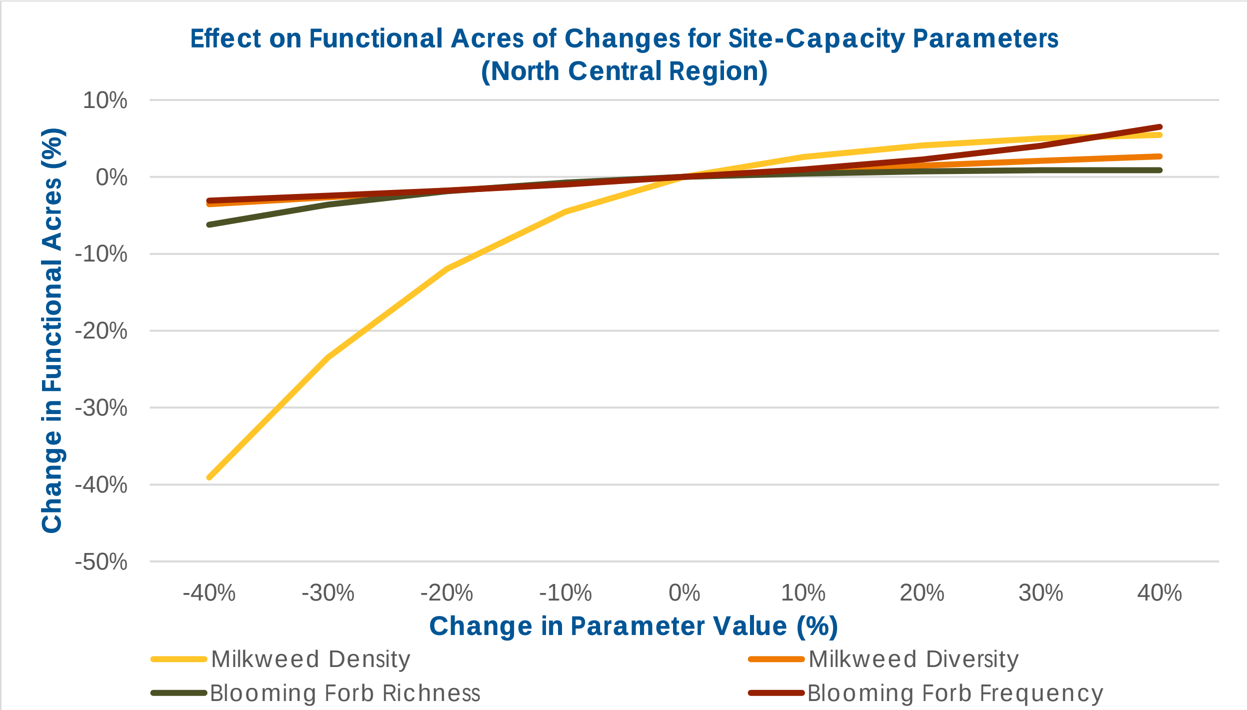

Figure 8. Sensitivity analysis for site-capacity parameters in the North Central region. The sensitivity of the HQT to marginal changes in each parameter value is represented by the slope of the line associated with that parameter. The mid-point between the minimum and fully-functioning value of the parameter is represented here as a 0% change in parameter value.

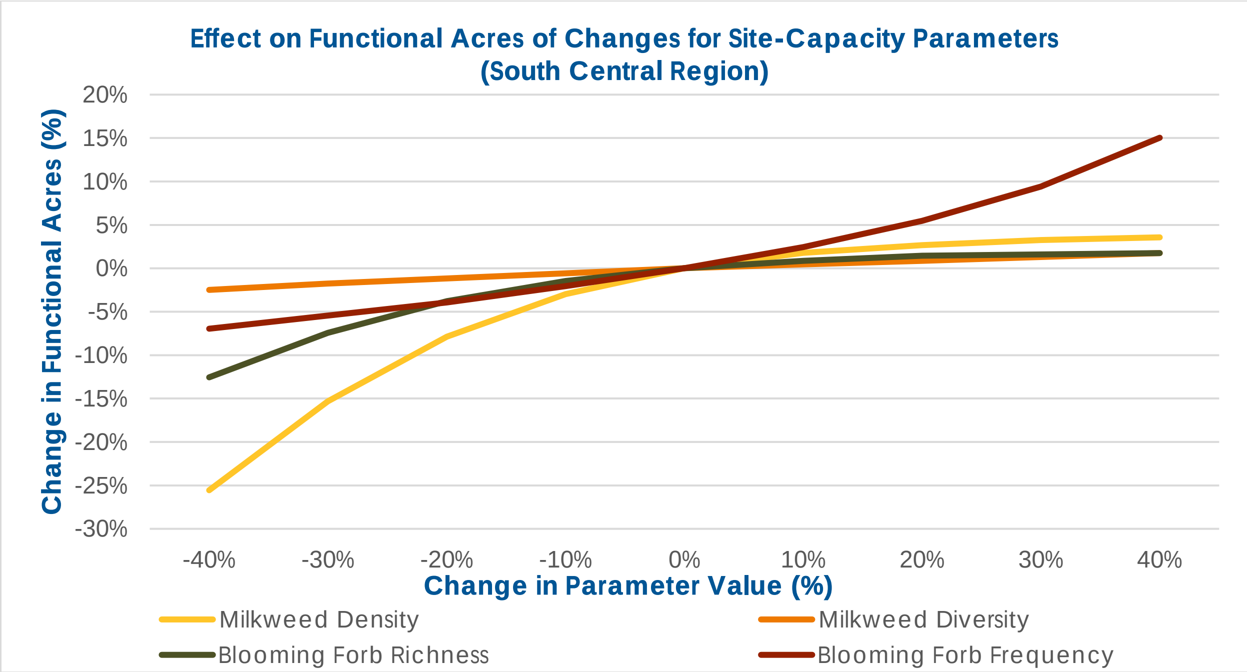

Figure 9. Sensitivity analysis for site-capacity parameters in the South Central region. The sensitivity of the HQT to marginal changes in each parameter value is represented by the slope of the line associated with that parameter. The mid-point between the minimum and fully-functioning value of the parameter is represented here as a 0% change in parameter value.

EXTERNAL REVIEW

External review of the Monarch HQT was sought from monarch experts and conservation practitioners in early 2017 and feedback provided has been incorporated in this version of the HQT to the extent practicable. External reviewers were asked to review each of the products in the HQT product set, including the Specifications document, User's Guide, and Calculator. Feedback was sought on both the scientific basis of the HQT and the usability for various use cases. A case study utilizing data collected during field testing was also provided to illustrate the HQT in practice. Improvements to the HQT based on feedback from monarch experts and users of the HQT should be incorporated in future versions of the HQT through adaptive management, as discussed in the following section.

ADAPTIVE MANAGEMENT

Much is still unknown about monarch butterfly biology, population dynamics, and response to habitat manipulation. For this reason and others, adaptive management of the HQT will be essential to the long-term efficacy of the tool and the Exchange. Adaptive management should be conducted in consultation with species experts, land managers, the Exchange Administrator, and other stakeholders on a regular basis. A plan for reviewing and updating the HQT with the best available science and knowledge gained from experience of using the HQT should be developed by each Exchange as soon as they are established. Adaptive management plans should consider: (1) accuracy of the HQT in measuring real and expected outcomes; (2) utility (ease of use, efficiency, and cost) for a variety of users; (3) repeatability of scores from one user to the next; and (4) reliability of scores over time. This section provides guidance for development and execution of an adaptive management plan.

Adaptive management is defined as the structured dynamic process of addressing uncertainty in management through the incorporation of procedures that seek to periodically revise and update tools, strategies and approaches to management in response to changing conditions or new information. Adaptive management strategies allow for changes to the overall conservation strategy to occur in response to changing conditions or new information, including those identified during monitoring. Adaptive approaches to management recognize that not all of the answers to management questions are known and some management is a process of trial and error. Adaptive management also includes, by definition, a commitment to change management approaches when appropriate for attaining biological goals and objectives of a conservation strategy. The goal of adaptive management for the HQT is to make periodic changes that keep it up to date with the current state of ecological knowledge.

The development of an adaptive implementation approach would address the following questions:

1. What criteria/metrics/data need to be collected over time?

2. How is this information incorporated into the HQT? What is the model framework within which these data are used to inform and adapt the HQT through time?
3. What are the steps and methods for implementing the HQT? Explicitly establish the steps along with cost estimates for implementing the HQT in a scientifically-rigorous manner.

A generalized process for implementing and adaptive approach is illustrated in Figure 10.

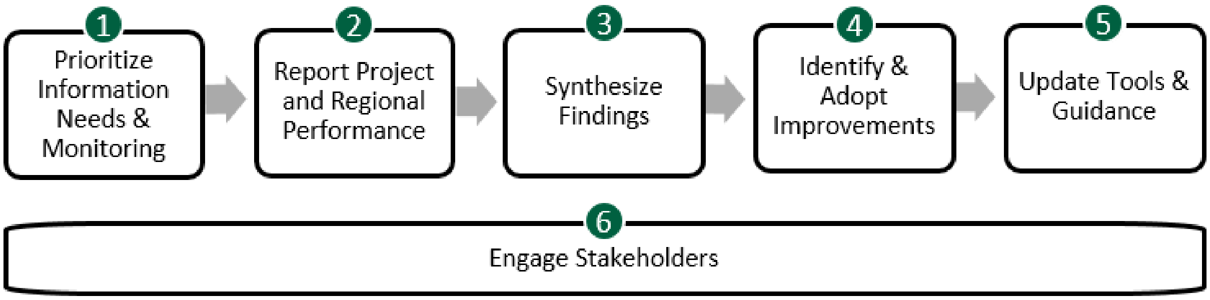

Figure 10. The adaptive management cycle defines a continuous improvement process for incorporating new information and updating the HQT with knowledge gained from experience using the HQT.

1. **Prioritize Information Needs and Monitoring**. The Exchange Administrator will identify and prioritize research and monitoring needs, coordinate funding efforts, and oversee monitoring and research aligned with the goals of the Exchange.
2. **Report Project and Regional Performance**. Routine reporting of accomplishments is essential to ensure transparency, inform learning and inspire confidence with stakeholders.
3. **Synthesize Findings.** Relevant research, monitoring and operational findings will inform ongoing learning and improve the Exchange.
4. **Identify & Adopt Improvements.** Operational and technical improvement suggestions and recommendations from species experts, land managers, and other stakeholders should be considered and adopted as appropriate by the Exchange Administrator to ensure the Exchange continues to operate efficiently and effectively over time.
5. **Update Tools & Guidance**. All necessary tools, forms, and guidance are updated to ensure practical experience and new scientific information results in increased efficiency and effectiveness.
6. **Engage Stakeholders**. Consistent and regular stakeholder engagement is necessary to ensure the Exchange operates efficiently, increases understanding, and cultivates the confidence of all stakeholders.

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APPENDIX A: OVERVIEW OF MONARCH BIOLOGY

Monarchs, like other butterflies and moths, have an egg, larva (caterpillar), pupa (chrysalis), and the mature adult stage. The egg and caterpillar stages occur only on species of milkweed (primarily in the genus *Asclepias*), whereas adults survive by foraging on a variety of flowering plants. Milkweed plants provide both food and shelter for monarch larvae for approximately two weeks (dependent on temperature).

Late fifth (and final) instar monarchs generally crawl away from the milkweed plants on which they were feeding to find a secure location to pupate. In 8 to 15 days, the adults emerge, and individuals in the non-migratory generations are sexually mature in about four days. These adults live approximately a month. Each fall, in the migratory generation, decreasing day length, increasing day:night temperature differences, and senescing milkweed trigger a change in monarchs (Goehring and Oberhauser 2002); most monarch butterflies that emerge after about mid-August in the eastern U.S. enter reproductive diapause (a state of delayed sexual maturity) and begin to migrate to overwintering locations. Unlike summer generations that live for two to six weeks as adults, adults in the migratory generation can live for up to nine months. These North American monarchs stay at overwintering sites for several months before re-migrating and breeding in the spring.

East of the Rocky Mountains, monarchs travel up to 3000 miles to central Mexico, whereas the western population overwinters both along the California coast and in central Mexico. There is evidence of some interchange between the eastern and western populations, perhaps when individuals cross the Rocky Mountains, when butterflies fly from the western U.S. to the Mexican wintering sites (Pyle 2015), or butterflies from the Mexican sites fly into the western U.S. There is also a small population of non-migratory monarchs in southern Florida that breed year-round, and some eastern North American butterflies remain along the Gulf Coast from Texas to Florida, also breeding during the winter. However, the vast majority of the eastern population overwinters in Mexico.

The most critical habitat requirements for monarch reproduction include milkweeds and nectar sources. Management strategies important to monarch habitat conservation include avoiding application of pesticides, prescribed burning to maintain habitat quality (during seasons that monarchs are not present), timely mowing (to avoid killing eggs and larvae), and exotic species control.

Eastern Monarchs Migratory Cycle

From across the eastern U.S. and southern Canada, monarchs funnel toward Mexico each autumn (Figure 10), using stopover sites with abundant nectar sources and roosting trees. Upon reaching their destination in central Mexico beginning in early November, they aggregate in oyamel fir trees on south-southwest facing mountain slopes in volcanic highlands. These locations provide cool temperatures, water, and adequate shelter to protect them from predators and allow them to conserve enough energy to survive winter. In March, this same generation begins the journey north into Texas and southern states, laying eggs and foraging as they migrate and breed. The first-generation offspring from the overwintering population continue the journey from the southern U.S. to recolonize the eastern breeding grounds, migrating north through the central latitudes in approximately late April through May. Second and third generations are produced in these breeding grounds throughout the summer. It is generally the fourth generation that migrates to the wintering sites in central Mexico.

Western Monarchs Migratory Cycle

Western monarchs roost in eucalyptus, Monterey cypress, Monterey pine, and other trees in groves along the Pacific coastline of California (Figure 10), arriving beginning in late October. The climate of these locations is similar to that of the Mexican overwintering locations. The colonies generally break up slightly earlier than those in Mexico, with dispersal beginning in mid-February. Less is known about the timing and location of breeding and migratory movement in the western U.S., but milkweed and nectar plant availability throughout the spring, summer and fall are important, especially in California, Nevada, Idaho, and Oregon, states that appear to be important sources of western monarchs (Stevens and Frey 2010). In areas of the desert southwest, monarchs reproduce throughout much of the year (Morris et al. 2015).

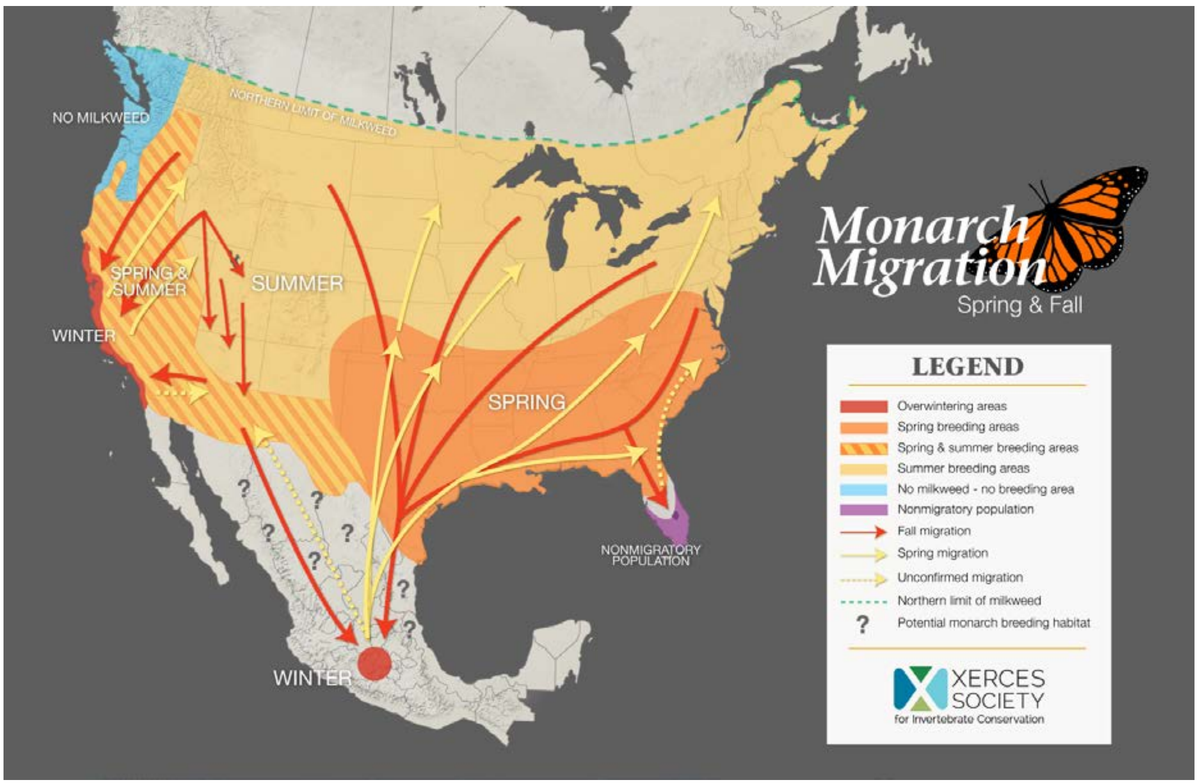

Figure 11. Fall migratory pathways represent the period from approximately late August through early November. Spring migratory pathways for the eastern population (the lines coming out of the Mexico wintering sites) represent approximately mid-March through May, and include egg-laying in the southeastern part of the U.S. The lines coming out of the southeastern U.S. represent movement by the offspring of the wintering generation into the summer breeding grounds. 2-3 additional generations are produced in these summer breeding grounds. Figure courtesy of Xerces Society.

APPENDIX B: OTHER FACTORS THAT AFFECT MONARCH PRODUCTION, SURVIVAL AND MIGRATION

The Monarch HQT prioritizes the key characteristics of monarch habitat that are both (1) primary drivers of monarch habitat suitability and (2) within the influence of decision makers (e.g., land managers). Predation, competition, extreme weather and climate change, among other factors, will all also affect monarch population levels, but they will not be assessed because they are largely outside of the influence of land managers. This section provides a discussion of the expected impacts of climate change and natural enemies on monarch populations.

Climate Change

Predicting species' responses to climate change is especially challenging for migratory species, like monarchs, because they could respond to climate change in two fundamentally different ways. First, because they depend on diverse resources across a vast landscape, and because the timing of migration is driven by environmental cues, migratory species could be especially vulnerable to environmental changes. On the other hand, their propensity to move could buffer them against shifting resources, with the outcome being little net change to their population sizes and distributions. Monarchs' response to climate change will also be driven by how milkweed responds; even if temperatures allow monarch survival, if conditions cause their milkweed host plants to go dormant, become too dry, or die altogether, monarchs will need to move to other areas.

Climate change models suggest that monarchs will need to move northward from their current range in June and July, and then return southward in August to track the conditions they currently use for reproduction (Batalden et al. 2007). Currently, only the spring generation appears to move northward before laying eggs, so this would represent a change from their current migratory pattern. Climate models also predict that the overwintering grounds in Mexico might be unsuitable for monarchs within this century, indicating that the eastern North American monarch population could require different overwintering habitat (Oberhauser and Peterson 2003, Ramirez et al. 2015). Whether monarchs can successfully overwinter in other areas depends in part upon their ability to survive the different weather regimes and different habitats present in areas such as the southern U.S.

To minimize the impacts of climate change, it is important to maintain corridors of suitable monarch and milkweed habitat, and ensure that other pressures on their populations are minimized.

The World Wildlife Fund and collaborators (Advani 2015) have developed a climate vulnerability report for monarchs.

Natural Enemies

Monarchs become toxic to most natural enemies by sequestering toxins from the milkweed they ingest as larvae, and are brightly colored in both the larval and adult stages to warn predators of this toxicity. Despite the fact that milkweeds are assumed to convey some degree of protection from generalist predators and parasitoids, monarchs of all life stages are vulnerable to predation and disease.

Monarch eggs and small larvae face considerable dangers of predation, and only about 5% of monarchs reach the last larval instar (reviewed by Oberhauser et al. 2015). Ants, spiders, true bugs, beetles, mantids, paper wasps, and lacewing larvae are some known predators of monarch eggs and larvae. Adults appear to face less predation pressure during the breeding season, but bird predators, especially the black-headed grosbeak, black-backed oriole, and Scott's oriole consume significant numbers of overwintering monarchs, with some additional predation by mice. In California, Rufous-sided towhees consume adult monarchs in overwintering clusters.

Parasitoids develop by feeding in or on a host organism, causing its eventual death. Monarch parasitoids are reported to include 12 species of tachinid flies, one chalcid wasp, and at least one braconid wasp. The best-studied monarch parasitoid is the tachinid fly *Lespesia archippivora*, which attacks larvae, resulting in the death of late-instar larvae or pupae. Some sites where tachinid fly parasitism has been studied have found parasitism rates of up to 90%, but the average rate is between 10 and 20% in the wild (Oberhauser et al. 2007). Unpublished data from the UM Monarch Lab documents parasitism by the tachinid fly *Compsilura concinnata*, a parasitoid that was introduced as a biological control agent to control gypsy moths (MLMP 2017); bio-control agents can have harmful non-target effects on beneficial species, like monarchs or other pollinators.

Recent studies have documented a pupal parasitoid of monarchs, *Pteromalus cassotis* (Stenoien et al. 2015). These tiny wasps lay eggs inside a monarch chrysalis, which emerge as adult wasps from the monarch pupa casing a few weeks later. Parasitism of monarchs by *P. cassotis* has been documented in MN, WI, TX, GA, and OK. *P. cassoits* has been documented without host records in several other states, including CA, so probably exists across much of monarchs' North American range. Observations of parasitism by *P. cassotis* are rare because they require finding chrysalids in the wild. However, when studied at overwintering sites in GA, parasitism can reach nearly 100% of pupae within a site (Stenoien et al. 2015).

McCoshum et al. (2016) developed ecological niche models using environmental data to identify areas with suitable abiotic conditions for eight known natural enemies of monarchs, including six predators: *Arilus cristatus, Harmonia axyridis, Monomorium minimum, Podisus maculiventris, Polistes* spp.*,* and *Solenopsis geminata*; and two parasitoids: *Lespesia archippivora* and *Pteromalus cassotis*. They combined correlated suitable areas for individual predators and parasitoids to identify regions with the most predator and parasitoid species potential. The Gulf Coast, West Coast, Florida, and parts of the eastern United States are predicted to have the most natural enemy species. These considerations have not been explicitly incorporated into this model, because they may have already been accounted for with other measures of survival. These findings may serve as useful starting points for further investigation of immature monarch survival that could augment future versions of the HQT ecological model.

Monarch larvae are generally found singly on milkweed plants, unlike the large aggregations of adults in overwintering clusters. Lower larval density in milkweed patches may reduce the chance of diseases, such as nuclear polyhedrosis virus and *Pseudomonas* bacteria, spreading between larvae. These diseases are often fatal to monarchs. A possible countermeasure to reduce impacts of these diseases is to increase the availability of large habitat patches.

Perhaps the most-studied parasite of monarchs is a protozoan parasite called *Ophryocystis elektroscirrha* (OE) (see review by Altizer and de Roode 2015). To become infected, larvae ingest dormant OE spores that fall from the abdomen of an infected adult to the surface of milkweed leaves or the egg. While it is often not fatal, OE can have negative effects on monarch survival, mass, and lifespan. There is a higher occurrence of OE in populations that do not migrate, such as the population in southern Florida. The eastern migratory population has the lowest occurrence of OE, likely due to the fact that infected monarchs are less likely to make it to their overwintering destinations in Mexico and therefore will not reproduce and spread the parasite. Recent studies about OE and exotic milkweed describe how the year-round presence of tropical milkweed in some parts of the U.S. may be facilitating the spread of this parasite (see above, and Satterfield et al. 2015).