RESEARCH ARTICLE

Trends in the Massachusetts cranberry industry create opportunities for the restoration of cultivated riparian wetlands

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Many ecosystem services provided by wetlands decline if they are managed for agricultural use. Ecological restoration of retired agricultural lands can restore these ecosystem services, yet practitioners require information on where restoration is possible and most likely to succeed. We report trends in the Massachusetts cranberry industry which suggest that cranberry farms located in riparian fens are well suited for ecological restoration that enhance their characteristics and functions as wetlands. We created a classification scheme for cranberry farms based on their: (1) crop status; (2) renovation status; (3) cultivar type; and (4) hydrologic type for the Wareham River watershed in southeastern Massachusetts. We ranked farms for their priority for restoration and extrapolated our results to the total cranberry acreage of Massachusetts. The occurrence of low-yielding native cranberry cultivars in all riparian farms (i.e. those with a direct hydrological connection to an adjacent river or stream), combined with our finding that 100% of the area of the highest-yielding new cultivars were planted in newly renovated but non-riparian farms suggest that riparian farms are not targets for investment but instead have a high likelihood of retirement. We found that 20% of farm area in this watershed had riparian hydrology, a proportion suggesting the existence of over 1,000 ha of high-priority farms for restoration statewide. Restoration of these stream-adjacent riparian farms can provide an exit strategy for some cranberry growers, ease economic pressures on remaining growers, and develop wetlands able to provide ecosystem services such as habitat provision, nitrogen removal, and recreation.

Key words: agricultural wetlands, cranberry, farmland abandonment, restoration, spatial analysis

Implications for Practice

- We propose an aerial imagery-based method for the classification of wetlands cultivated for cranberries based on their: (1) crop status; (2) renovation status; (3) cultivar type; and (4) hydrologic type.
- Trends in farm renovations and cultivar distribution suggest that the Massachusetts cranberry farm acreage can be partitioned into three ranks based on their likelihood for retirement and restoration, with the highest priority sites being traditionally constructed farms located adjacent to rivers that are planted with low-yielding native cultivars.
- Riparian farms represent the most attractive sites for retirement, permanent land protection, and ecological restoration because of their lower yields, challenging management, and potential to offer ecosystem services such as habitat provision, nitrogen storage and removal, and recreation.

Introduction

The retirement of farmland now occurring in many high-income and urbanizing nations presents potential opportunities for ecological restoration (Whitney 1994; Comin et al. 2001; Lee et al. 2002; Moreira & Russo 2007; Chazdon 2014; Queiroz et al. 2014). The forces that influence farmland retirement and the potential fate of retired farmland differ widely based on economic and geographic contexts (Poore 2016; Stewart et al. 2019), yet these trends can be used to develop specific restoration programs. Conservation and restoration practitioners can observe trends in land-use change using remote sensing in order to identify and prioritize sites for land protection (Moreira & Russo 2007; Gimmi et al. 2011), particularly sites with the potential to offer valuable ecosystem services and that may otherwise be developed for industrial, commercial, or residential use.

The American cranberry (Vaccinium macrocarpon Ait.) has been cultivated in the northeast United States since the early nineteenth century (Eastwood 1856; White 1885) but is

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now also cultivated in the U.S. Upper Midwest and Pacific Northwest, as well as globally in Canada, Chile, and several Baltic states. Modern cultivation began on Cape Cod in Massachusetts (Eastwood 1856; White 1885), and today, cranberry remains Massachusetts’ highest value food crop with an economic footprint for cultivation, support, and processing estimated at $1.4 billion (Massachusetts Department of Agricultural Resources [MassDAR] 2016). However, since about 2000, cranberry cultivation in Massachusetts has become less profitable because of factors including, but not limited to, oversupply, low cranberry prices, and competition with growers in the Upper Midwest and Canada who have access to relatively inexpensive developable land on which they have created new cranberry farms using modern construction methods and plantings of newer, high-yielding hybrid cultivars. These economic conditions are pushing some Massachusetts cranberry growers to either increase yields by modernizing existing farms and planting new hybrid cultivars, or retire farms and exit the industry (MassDAR 2016).

The American cranberry is found naturally in cool, moist, and organic-rich peat soils across southern Canada from Newfoundland to Ontario, and in the United States from New England to the Upper Midwest (Eck 1990; Sandler 2008a). In Massachusetts, cranberries often grow in peat deposits located in postglacial depressions (Johnson 1985; DeMoranville 2008a), such as in fluvigeneous (or riparian) fens adjacent to coastal rivers, soligenous (or non-riparian) fens fed primarily by groundwater, and ombrotrophic bogs fed primarily by precipitation (Wassen et al. 1996; Mitsch et al. 2007; Rochefort et al. 2012; Masterson & Walter 2009). The majority of Massachusetts cranberry farms are located in peatlands (Kennedy et al. 2018a), in part because the autochthonous peat contributes to acidic and moist soil conditions under which the American cranberry grows favorably (Sandler 2008a). The peat also acts as a water confining layer that minimizes nutrient leaching and can hold floodwater for harvest and winter cold protection (Eck 1990; DeMoranville 2008a).

Cranberry cultivation requires the management of farm hydrology and soil conditions to promote fruit production (DeMoranville 2008b). Water supply is controlled through a balance between sprinkler irrigation and water drainage through a system of canals, ditches, and berms that divide the cranberry farm into separate management units. Each unit of cranberry vines is grown in a layer of allochthonous sand, amounting up to 50-cm over several years of successive layering (Kennedy et al. 2018a), to promote root aeration, plant growth, and drainage (DeMoranville 2008a). Growers may influence nearby surface waters by constructing bypass canals and reservoirs, and by using adjacent rivers and lakes as water sources or discharge points (DeMoranville 2008b).

Management is influenced by the hydrology of the farm, and cultivation practices and water management infrastructure vary among farms located in riparian fens, non-riparian fens and bogs, or non-wetland upland regions. Cranberry farms located in riparian fens are widely referred to as “flowthrough” farms in the northeast United States (Howes & Teal 1995; DeMoranville 2008a) and feature a large continuously flowing stream channel as their central drainage canal. Cranberry farms that do not receive surface water inputs except for irrigation and managed floods may be fens or bogs depending on the elevation of the farm and the height of the regional water table. Many recently constructed cranberry farms are located in upland regions where the hydrology and soil structure are engineered to produce conditions suitable for cultivation. Upland farms often feature a clay underlayer that replaces autochthonous peat as the water-confining layer (DeMoranville 2008a). In this study, we refer to farms located in uplands, non-riparian fens, and bogs as having “non-flowthrough” hydrology because the continuously flowing stream channel in flowthrough farms significantly alters its hydrology and water management relative to farms without a stream channel.

While cranberry farms are still legally considered wetlands (Hollands 2008), due in part to the frequent soil inundation and the presence of cranberry, an obligate wetland plant (Native Plant Trust 2019), cranberry farms nonetheless represent cultivated wetlands which are highly modified and intensely managed. The hydrology and soil conditions of the wetland are modified and the disturbance regime managed in order to maximize food crop production.

As cranberry production becomes less profitable and some farms are retired, legacies of cultivation remain. The water management infrastructure and anthropogenic sand layer persist after farm retirement and continue to influence the hydrology and soil conditions of the wetland for many years to come (Suding et al. 2004; Cramer et al. 2008; Chimner et al. 2017). The potential impoverishment of native seed banks and competition with established cranberry vines and invasive exotic species may also influence the establishment of native wetland plants and the development of biodiversity (Suding et al. 2004; Cramer et al. 2008; Morimoto et al. 2017). These abiotic and biotic legacies of cultivation motivate investments in pro-active restoration measures to promote more desirable post-retirement ecosystem characteristics, functions, and services than may otherwise develop under passive naturalization (Suding et al. 2004; Cramer et al. 2008; Chimner et al. 2017).

The ecosystem services targeted during the ecological restoration of a retired cranberry farm depend on the capacity of a site to offer a particular service as well as the desirability of competing services to stakeholders. For example, nitrogen attenuation, a commonly targeted ecosystem service in wetland and river restoration (Comin et al. 2001; Craig et al. 2008; Palmer et al. 2014), may be more attainable and most valuable for a restored cranberry farm located in a fen which receives significant anthropogenic nitrogen inputs, such as from the effluent of a waste water treatment plant (Böhlke et al. 2002). In contrast, a restored farm may have less impact on watershed nitrogen loads if it is located in an ombrotrophic bog far from any major anthropogenic nitrogen inputs. This latter hypothetical cranberry farm, however, might still be suitable for a restoration project targeting biodiversity and landscape connectivity even if it is not suitable for mitigating nitrogen pollution. Hence, some cranberry farms may be more or less amenable for restoration, or for particular restoration goals, depending on their hydrology, management legacy, and geographic context.
Restoration of cranberry farms could offset a portion of the approximately 93,000 ha of wetlands in Massachusetts that were lost between 1780 to the mid-1980s (Dahl 1990), and the associated wetland ecosystem services including habitat provision, nitrogen attenuation, floodwater storage, and recreation which were lost as a result (Reddy et al. 1984; Johnston 1991; Mitsch & Gosselink 2000; Millennium Ecosystem Assessment 2005; Euliss et al. 2008). Site-specific characteristics, such as the presence of a stream channel or nearness to population centers, constrain the potential goals and designs of restoration projects. Current economic hardship for growers in Massachusetts and the presence of competing land development pressure in this quickly growing region additionally mean that restoration advocates must be strategic in selecting sites for land protection and potential restoration.

In Massachusetts, a Legislative Task Force concluded that the protection and restoration of cranberry farms to natural wetlands should be promoted as an “exit strategy” for willing cranberry growers (MassDAR 2016). In response to the state of the cranberry industry and the potential for the ecological restoration of retired farmland, the Massachusetts Department of Fish and Game’s Division of Ecological Restoration (MassDER) in 2018 created a new program focused solely on wetland restoration in retired cranberry farms (MassDER 2019).

Because funds for these programs are limited and over 2,000 ha of active farms are thought to be vulnerable to retirement in the near-future (MassDAR 2016), it is important to understand: (1) what characteristics of a cranberry farm’s hydrology or management legacy, if any, are common among cranberry farms that are already retired? (2) how we can predict the likelihood of a cranberry farm being retired in the near future on the basis of these characteristics? and (3) how do these characteristics inform the prioritization, design, and goals of ecological restoration projects in retired cranberry farms?

To investigate how the characteristics of cranberry farms may influence the potential for farm retirement, land protection, and ecological restoration in southeastern Massachusetts, we combined aerial imagery, publicly available spatial data, and agro-nomic data obtained from local cranberry growers. We classified and estimated the aerial extent of cranberry farms based on their crop status as actively cultivated or retired, type of farm construction, and planted cranberry cultivar. We also evaluated if farms featured a major stream channel connected to surrounding surface waters. We estimated the aerial extent and proportions of farms within these intersecting categories in order to elucidate trends between farm characteristics, grower practices, and farm retirement. Finally, we indicated how these trends will create opportunities for land protection and inform the prioritization, design, and goals of future restoration projects.

Methods

Study Area

We characterized the cranberry industry in the Wareham River watershed (Fig. 1) because of its environmental and economic significance in southeastern Massachusetts (Howes et al. 2014). The Wareham River watershed ranks second in the total state area of cranberry farms (Williamson et al. 2017) and serves as an appropriate model of the trends in the Massachusetts cranberry industry in general. This watershed represents the fourth largest nitrogen contributor to Buzzards Bay (Fig. 1), an estuary that receives freshwater drainage from several river basins in southeastern Massachusetts and Cape Cod (Costa 2013; Williamson et al. 2017). Coastal eutrophication is a major concern for Buzzards Bay and reducing watershed nitrogen sources is an important motivation for wetland restoration.

We determined the boundaries of the Wareham River watershed based on the U.S. Geological Survey (USGS) Plymouth-Carver-Kingston-Duxbury Aquifer groundwater model (Masterson et al. 2009) and refinements made by the Massachusetts Department of Environmental Protection (Mass-DEP) in collaboration with the USGS and the University of Massachusetts Dartmouth (Howes et al. 2014).

Spatial Classification and Analysis

We based our analysis on existing MassDEP ArcGIS (v. 10.6) layers for active and retired cranberry farms within the Wareham River watershed (Jim McLaughlin 2013, personal communication; MassDEP, personal communication). See Appendix S2 for more details on the spatial analysis. We classified farms according to four criteria:

1. Crop status: is the cranberry farm actively managed or is it retired?
2. Renovation status: is the cranberry farm newly constructed, recently renovated, or of a historic/traditional construction?
3. Cultivar type: what is the current planted cultivar?
4. Hydrologic type: does the cranberry farm have flowthrough or non-flowthrough hydrology?

Crop Status

Crop status was initially classified as active or retired by Mass-DEP in 2013. We then updated the 2013 assessment with farms that were recently retired if there was obvious tree cover within the farm (a clear indicator of inactivity) according to 2018 Google Ortho Imagery (MassGIS 2018).

Renovation Status

We classified renovation status based on Google Earth Pro historical imagery available from 1995 to 2018. Newly constructed farms were those constructed in upland regions adjacent to existing cranberry operations that did not replace an already-present farm. Renovated farms were those that underwent a renovation as evident from comparisons of different years of Google Earth imagery. Farms were considered renovated if they were re-sanded, re-planted, and both the outer perimeter and interior ditch systems were altered between 1995 and 2018 (Fig. 2). The starting year of new construction or renovation was noted for all farms, and we assigned renovations occurring during gaps in the available aerial imagery (1995–2001 and 2012–2014) to the midpoint of the available years. We classified farms with...
Cranberry farms are color-coded according to their classification as retired (red), flowthrough (blue), non-flowthrough with traditional construction (purple), and non-flowthrough with renovated or new construction (green). Colors roughly correspond to our ranking of the likelihood of retirement: Rank I (blue), rank II (purple), and rank III (green). Water from the White Island pond subwatershed (gray boundary) discharges to Buttermilk Bay (Eichner et al. 2012; Howes et al. 2014) while the fate of discharge from Halfway pond and College pond subwatersheds (dashed black boundary) is unclear. See Appendix S1 for more discussion of the uncertainties in watershed delineations. Aerial imagery is from Google Ortho imagery (MassGIS 2018).
Table 1. Typical fruit sizes, yields, and recommended nitrogen fertilization rates for the cultivars within each of our defined cultivar groups. Note that while the ‘Ben Lear’ variety is in fact a wild cultivar native to Wisconsin rather than a hybrid, its yield and berry size is more akin to other first generation hybrids than ‘Early Black’ or ‘Howes’ cultivars and is therefore categorized as such. The listed cultivars for the first and second generation hybrids are not exhaustive and only include those reported to the authors by growers in the region. See Appendix S3 for description of data sources.

| Tier Name               | Cultivars                               | Average Fruit Size (g) | Average Yield (Mg/ha) | Recommended N Application Rate (kg N/ha) |
|-------------------------|-----------------------------------------|------------------------|-----------------------|------------------------------------------|
| Natives                 | Early Black, Howes                      | 0.9                    | 16                    | 28–45                                    |
| First generation hybrids| Ben Lear, Stevens, Grygleski, Pilgrim   | 1.6                    | 25                    | 39–56                                    |
| Second generation hybrids| Crimson Queen, Mullica Queen, DeMoranville | 2.3                    | 31                    | 56–90                                    |

2018 active farm area in the Wareham River watershed. Cultivar tiers were defined according to their average fruit yield and size: (1) Massachusetts native cultivars including ‘Early Black’ and ‘Howes,’ (2) first generation hybrid cultivars including ‘Stevens’ and the wild large fruit variety ‘Ben Lear’ native to Wisconsin, and (3) second generation “super” hybrid cultivars such as ‘Crimson Queen’ and ‘Mullica Queen’ (Table 1). Reports of cultivar plantings were new as of 2017 and on the scale of individual farm units, thereby allowing direct linkage between the planted cultivar of a farm and its observed renovation status and hydrologic type. We assumed that the cultivar distribution of these growers was representative of the Wareham River watershed in general and applied the proportions of cultivar tiers within the categories of farm renovation statuses and hydrologic types to the remaining 42% of active farm area for which we did not have cultivar data.

Hydrologic Type
We classified hydrologic types based on visual evaluation of aerial imagery and comparison of farm location with nearby hydrological features. We classified farms as flowthrough if there was a large central channel (usually heterogeneous and meandering), farm units on either side of the channel, and connected hydrological features (e.g., streams, ponds, or wetlands) both up- and down-gradient from the growing operation (Fig. 3). The presence of connected hydrological features was assessed using the MassDEP Hydrogeography layer (MassGIS 2017). We required these adjacent hydrological features in our classification so as to only include farms located in riparian fens that are intimately connected to nearby surface waters. Farms classified as non-flowthrough therefore represent peatlands relatively more isolated from surface waters (i.e. non-riparian fens and bogs) as well as non-wetland uplands.

Prediction Assumptions
To predict future farm retirement based on the results of our spatial analysis, we made two assumptions. We assumed that cranberry farms will be, on-average, less likely to retire in the near future: (1) the more capital a grower invests in a farm

![Figure 2. Example of a farm classified as “renovated.” Note the highly altered outer perimeter and ditch systems, as well as the laying of new sand and planting of a new crop. Image retrieved using Google Earth.](image)
Restoration of cultivated wetlands

Figure 3. Example of a farm classified as featuring “flowthrough” hydrology. Note the large and heterogeneous channel, the presence of farm units on either side of the channel, and the connectivity with ponds on either side of the channel. Image retrieved using Google Earth.

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cultivars (Sandler 2008). Renovations primarily include those
captureredinouranalysis,thatis,reesandingofthefarmunit
andupgradestothe ditch and canalsystem,as well as relatively
more minor renovations that we were unable to observe, such
as upgrades to irrigation systems, bypass canals, or receiving
ponds. While we omitted these renovations in our analysis, we
nonethelsscaptures themostexpensive renovations and those
that most significantly impact management and yields. Planting
a first or second generation hybrid cultivar also increases yields,
however,expensive renovations costing up to $82,000/ha must
accompany a new planting (MassDAR 2016). The high cost of
renovations and new plantings, as well as the improved
management efficiency and yields which follow, mean that growers
are unlikely to retire farms that received recent renovations or
plantings of hybrid cultivars. We also considered farms newly
constructed in upland regions as being unlikely to be retired
because of the grower’s recent investment and likely use of mod-
ern construction methods and hybrid cultivars.

Management issues also influence the likelihood of retire-
ment. The presence of a continually flowing stream channel in
flowthrough cranberry farms is a water management challenge
not present in non-flowthrough farms in which surface water
inputs can be more easily controlled. It is also more difficult
tomanage nutrients and pests in flowthrough farms and there
is evidence that they export more nitrogen to surface waters
compared with non-flowthrough farms (Howes & Teal 1995;
Kennedy et al. 2018b; Neill et al. 2017). Because of manage-
ment challenges and lower yields, we assumed that farms fea-
turing flowthrough hydrology are more likely to be retired than
non-flowthrough farms.

We therefore assumed that farms featuring: (1) traditional and
un-renovated construction; (2) plantings of native cultivars; and
(3) flowthrough hydrology are, on-average, more likely to be
retired than renovated or newly constructed farms planted with
hybrid cultivars located in a non-riparian fen, bog, or upland.
We tested these assumptions by comparing the characteristics of
farms that were already retired as of 2018 and by corresponding
with local growers to learn which farms they intend to retire in
2019. Since our classification derived from spatial and cultivar
data originating in 2017 and 2018, an independent account of
newly retired farms in 2019 served to validate our retirement
predictions.

Extrapolation to Massachusetts

We extrapolated our results within the Wareham River water-
shed to the total cranberry farm area of Massachusetts to esti-
mate the area of farms that might be retired and available to
be restored in the future. The proportions of farms within the
intersectingcategories of crop status, renovation status, culti-
var type, and hydrologic type in the Wareham River watershed
were applied to the 5,486 ha of fruit-bearing cranberry farms in
Massachusetts in 2017 (USDA NASS 2017).

Results

Spatial Analysis in the Wareham River Watershed

We found 675 ha of active cranberry farms and 24 ha of retired
cranberry farms in our analysis, compared to 686 ha of active
farms and 8 ha of retired farms reported by MassDEP in 2013
(Table 2). This represented a 1.6% decline in active area (loss
of 11 ha) and a 173% increase in retired area (increase of
14.5 ha) over 5 years. Decreases in active area and increases
in retired area were not equivalent because renovations slightly

Table 2. Total areas of cranberry farms in the Wareham River watershed according to classification by (1) crop status; (2) renovation status; and (3) hydrologic type. Percentages represent the proportion of the class out of the total 675 ha of active cranberry production.

| Category           | Area (ha) | Percent of Total Area (%) |
|--------------------|-----------|---------------------------|
| Active acreage     | 675       | 100                       |
| Retired acreage    | 24        | —                         |
| Traditional        | 473       | 70                        |
| Renovated          | 170       | 25                        |
| Newly constructed  | 32        | 5                         |
| Non-flowthrough    | 542       | 80                        |
| Flowthrough        | 133       | 20                        |

Figure 4. Plot of the total areas of renovated and newly constructed farms each year from 1995 to 2018 in the Wareham River watershed, as well as the Massachusetts (MA) cranberry yields reported to the USDA NASS. Areas represent the perimeter of the finished farm rather than pre-renovated farm, while the year relates the first year the construction began as evaluated using Google Earth. Renovations and new constructions during gaps in the historic imagery were assigned to the midpoint of the gap. A gap in imagery from 1995 to 2001 and the large amount of renovations observed over this period resulted in the large renovation value for the midpoint year of 1998. Yields are given as $10^3$ kg of harvested fruit per hectare of actively cultivated farm on a statewide basis.

Figure 5. Proportion of active cranberry farm area planted with native, first generation hybrid, or second generation hybrid cultivars for (A) Massachusetts Ocean spray growers in 2012 (MA OS 2012), Massachusetts Ocean spray growers in 2015 (MA OS 2015), and growers enrolled in ocean spray located in the Wareham River watershed in 2017 (MA OS 2017); (B) farms within the MA OS 2017 acreage which we classified as being traditionally construction, renovated, or newly constructed; and (C) farms within the MA OS 2017 acreage which are classified as non-flowthrough or flowthrough. Note that proportions given for (B) and (C) related to renovation status and hydrologic type are for the 358 ha of acreage for which we have cultivar data (i.e. the MA OS 2017 cultivar data) and not proportions by category for the entire 675 ha acreage of the watershed.

Of the active farm area, 70% was traditional farms, 25% was renovated farms, and 5% was newly constructed farms (Table 2). We found that 18% of the area of renovated and new farms was constructed before 2005 and 82% was constructed after 2005 (Fig. 4). Massachusetts cranberry yields increased from 2006 to 2016 as the area of renovated and newly constructed farms increased (Fig. 4).

We found that 46% of active farm area was planted with native cultivars, 39% was planted with first generation hybrids, and 15% was planted with second generation hybrids (Fig. 5A). Cultivar distribution from earlier grower reports showed 71% of statewide area planted with native cultivars in 2012 and 55% in 2015, showing a clear trend of declining statewide use of native cultivars (Fig. 5A; Joe DeVerna, Ocean Spray, personal communication). Native cultivars were planted in 76% of traditionally constructed farm area whereas no newly constructed or renovated farms were planted with native cultivars (Fig. 5B). Of the total area planted with the highest-yielding second generation hybrids, 93% was in renovated farms.

Figure 5. Proportion of active cranberry farm area planted with native, first generation hybrid, or second generation hybrid cultivars for (A) Massachusetts Ocean spray growers in 2012 (MA OS 2012), Massachusetts Ocean spray growers in 2015 (MA OS 2015), and growers enrolled in ocean spray located in the Wareham River watershed in 2017 (MA OS 2017); (B) farms within the MA OS 2017 acreage which we classified as being traditionally construction, renovated, or newly constructed; and (C) farms within the MA OS 2017 acreage which are classified as non-flowthrough or flowthrough. Note that proportions given for (B) and (C) related to renovation status and hydrologic type are for the 358 ha of acreage for which we have cultivar data (i.e. the MA OS 2017 cultivar data) and not proportions by category for the entire 675 ha acreage of the watershed.

**Assumption Validation**

Of the 24 ha of retired farms in 2018, 10 ha or 40% featured flowthrough hydrology. We additionally learned of the new retirement of 34 ha of cranberry farms in 2019 from a group of growers in the Wareham River watershed. We independently classified 5 ha of this 34 ha subset as already retired in 2018 due to the presence of trees. Of the 34 ha of new retirements, 32 ha or 96% were planted with native cultivars and 28 ha or 83% featured flowthrough hydrology.

These results illustrate that tree coverage is a viable predictor for cranberry farm retirement and that growers preferentially retired farms planted with native cultivars and that featured flowthrough hydrology. These assumptions were also supported by the selection by the State of Massachusetts (as of 2019) of only flowthrough cranberry farms for government investment in active restoration projects (the Eel River, Tidmarsh Wildlife Sanctuary, and the Coonamessett River).
Table 3. Proportions of farm area in ranks according to their priority for retirement and restoration in the Wareham River watershed and the state of Massachusetts. Proportions derive from analysis in the Wareham River watershed and were then applied to the 5,486 ha of active cranberry farms in Massachusetts (USDA NASS 2017).

| Rank     | Characteristics                          | Percent of Area (%) | Area in the Wareham River Watershed (ha) | Area in Massachusetts (ha) |
|----------|------------------------------------------|---------------------|-----------------------------------------|---------------------------|
| I. High  | Flowthrough, traditional construction, native cultivars | 20                  | 133                                      | 1,077                      |
| II. Moderate | Non-flowthrough, traditional construction, native cultivars | 35                  | 235                                      | 1,913                      |
| III. Low | Non-flowthrough, hybrid cultivars         | 45                  | 307                                      | 2,496                      |
| Total    |                                         | 100                 | 675                                      | 5,486                      |

Farm Retirement Predictions

From the above classifications, we derived three ranks of cranberry farms based on their likelihood for retirement in the near future (Table 3). Rank I represented the most likely candidates for retirement: the 20% of farm area that featured flowthrough hydrology, while Rank III represented the least likely candidates for retirement: the 45% of farm area that was renovated or newly constructed and planted with first or second generation hybrid cultivars. Rank II represented the 35% of intermediate cases of un-renovated non-flowthrough farms planted with native cultivars which might be retired or renovated in the future.

Application of the proportions of farms in each rank within the Wareham River watershed to the total cranberry farm area of the state of Massachusetts yielded over 1,000 ha of flowthrough farms in the high-priority Rank I, and nearly 2,000 ha in Rank II (Table 3). Almost half, or 2,500 ha, of the state acreage was in the low-priority Rank III.

Discussion

Trends in Farm Characteristics and Retirement

Our predictions of farm retirements align with industry expectations that, under current trajectories, more than 2,000 ha of active farms may be vulnerable to retirement (MassDAR 2016). Farm retirement in Massachusetts as of 2018 is distributed unevenly among farms featuring different renovation statuses, planted cultivars, and hydrology, suggesting that retirement is driven chiefly by the typically lower profitability of farms in Rank I that are unrenovated, planted with native cultivars, and feature a continuously flowing stream channel. Farms in Rank III, which are located in non-riparian fens, bogs, or uplands, and have recent investments in renovations or hybrid cultivars, represent a more profitable and growing category of farms in Massachusetts. We anticipate that many farms in Rank II will be renovated and planted with new cultivars in the near future, even if some do retire. Our results suggest ongoing decisions by growers to renovate and plant new cultivars on those farms with the greatest potential to compete in this new economic landscape.

We classified farms on the basis of their hydrology to predict farm retirement as well as to refine regional watershed nitrogen load models (Howes et al. 2014; Williamson et al. 2017). The wide variation in watershed nitrogen loading rates estimated to be contributed by flowthrough versus non-flowthrough farms (Howes & Teal 1995; DeMoranville & Howes 2005; Neill et al. 2017; Kennedy et al. 2018b), and the use of regional flowthrough farm areas and their particular nitrogen loading rates as model inputs motivate the development of robust remote image-based classification methods.

Our proportion of flowthrough farms of 20% was less than the ~30% commonly cited for the southeastern Massachusetts region. In a 1988 questionnaire to Massachusetts growers by the USDA, growers representing approximately 64%, or 3,062 ha, of the total 4,832 ha of producing farms in the state at that time reported that 34% of total farm area consisted of flowthrough farms (USDA SCS 1988). Howes et al. (2014) reported a similar proportion of 30.7% based on aerial imagery and the 2013 MassDEP cranberry layer. We attribute this 10% decline to differences in the stringency of classification and the retirement of multiple flowthrough farms in this watershed over the last 50 years.

Uncertainties in Farm Classification

Several potential uncertainties could have influenced our farm classifications. Our estimate of total retired farm area was likely a slight underestimate because of our reliance on tree colonization to indicate farm retirement. Recently retired farms may not have significant tree colonization for several years, while farms retired for multiple decades develop tree stands often indistinguishable from adjacent forests. However, our classification of 5 ha of retired farmland in 2018 on the basis of tree cover, which were then independently verified as retired in 2019, supported the validity of our method.

Our classification of renovation status yielded a conservative estimate of the area of renovated farms because we did not account for renovations that did not produce visually recognizable changes in the growing operation. Our conservative estimate of the total area of renovated farms may have resulted in an overestimation of the area of un-renovated farms that may be renovated or retired in the near-future (Rank II).

The lack of comprehensive cultivar data for the entire watershed motivated our assumption that the distribution of cultivars within the subset of growers representing 58% of the area was representative of the remaining 42%. Our cultivar data come from growers operating cranberry farms larger than the typical independent grower in Massachusetts, so it is likely that, on average, they adopted hybrid cultivars more quickly and to a greater extent than the rest of the watershed. It is therefore possible that we overpredict the extent of hybrid cultivar adoption in the state of Massachusetts.
Our stringent criteria for classifying flowthrough farms may have resulted in a conservative estimate of total flowthrough area, however, our criteria are consistent with previous characteristics of flowthrough farms (Howes & Teal 1995). The binary categorization of hydrologic type as “flowthrough” or “non-flowthrough” fails to recognize the wide variation in soil and hydrology between non-flowthrough farms in bogs, fens, bogs, or uplands. However, this simplification was deemed appropriate for our analysis on the basis that the difference in hydrology between flowthrough and non-flowthrough farms was easily distinguishable through remote sensing and more relevant for predicting farm retirement than differences within the non-flowthrough category.

Comparison of our flowthrough classification method with prior surveys is made challenging by the fact that workers typically do not provide a precise description of what characteristics define a flowthrough farm or what protocol was used to evaluate individual sites. Imagery-based methods as used by Howes et al. (2014) and in the current study are advantageous due to low labor costs and rapid results. However, bias from the individual GIS worker can influence the classification, particularly for borderline or ambiguous cases, and not all of the hydrological complexity of a site can be captured with a single top-down image. Grower reports such as the 1988 USDA questionnaire address this latter concern given the growers’ intimate knowledge of their farms; however, questionnaires of this type are labor-intensive, susceptible to sampling bias, and there is no certainty that growers have uniform conceptions of what a “flowthrough” farm is.

Future regional predictions should include more grower questionnaires and integrate additional spatial data, such as maps of soil type, water table height, or topography. However, to understand the hydrology of a particular site to the level required for the design of a restoration project, workers must employ field observations and measurements in addition to remote sensing.

Opportunities for Restoration

The loss of wetland area since pre-settlement (Dahl 1990) and the rapid population growth of eastern Massachusetts motivates efforts to protect retired farmland from alternative land development. The limited amount of federal, state, local, and private funds available for conservation and restoration means that advocates must prioritize sites for protection, ideally on the basis of information available quickly and at a low cost. We propose our classification method as one basis for site selection and prioritization, with the intent that the hydrologic type of the farm be considered. Flowthrough farms, in particular, represent not only the most-likely candidates for retirement, they also represent sites which could develop into high-functioning riparian wetlands through ecological restoration.

Pro-active restoration methods are required to develop wetland characteristics and functions because of the persistent influence of landscape modifications on the soil structure and hydrology of the former farmland (Suding et al. 2004; Cramer et al. 2008; Chimner et al. 2017). The anthropogenic sand layer, ditches, and canals promote drainage and lower the water table (Ketcheson & Price 2011; McCarter & Price 2013), resulting in moist but well-drained soil conditions rather than the frequent or constant inundation that favors wetland plants. In flowthrough farms, aquatic plant and animal communities may also be impacted by the altered channel morphology and flow regimes of channelized and segmented streams (O’Hanley et al. 2013). Topographical variation is absent in the leveled farms (Sandler 2008b) and connectivity between farm units and the surrounding landscape is hindered by the presence of berms. While retired but unrestored cranberry farms may spontaneously develop into novel ecosystems defined in part by these legacies of cultivation (Higgs 2017; Klee et al. 2019), recovery of some desirable wetland characteristics and functions may require active restoration methods.

Three restoration projects have been completed in former cranberry farms so far in the state of Massachusetts: the Eel River in Plymouth, MA in 2010; Tidmarsh Wildlife Sanctuary in Plymouth, MA in 2016; and Lower Bog in the Coonamessett River in Falmouth, MA in 2018 (MassDER 2019). All three sites were former flowthrough cranberry farms and they now amount to approximately 90 ha of restored wetlands. The primary restoration activities included removing culverts, berms, and much of the anthropogenic sand layer, roughing the surface to create hummocks and hollows, plugging ditches, and removing unwanted plants, particularly mature trees and invasive exotics. The central drainage canals, formerly straightened and channelized for cultivation, were naturalized through the construction of meanders, tributaries, and connecting ponds. These activities created hydrologic and soil conditions suitable for developing a diverse wetland plant community and providing habitat for birds, insects, and amphibians. The stream naturalization in the Coonamessett River also aimed to restore historic herring populations impaired by the damming and channelizing of the former un-restored stream channel. Finally, all three sites were designed with the hope of promoting watershed nitrogen attenuation through denitrification and biological uptake processes in the restored wetlands. Monitoring of plant succession, soil characteristics (Ballantine et al. 2017), and water chemistry in these sites is ongoing.

Compared to the nearly 1,000 ha of flowthrough farms in Rank I which may be vulnerable to retirement in the near future, three completed projects and 90 ha over nearly a decade has been a modest response to a currently large opportunity for wetland restoration. According to MassDER, seven projects representing over 200 ha of farmland were in the design and permitting phase as of 2019 while another 13 potential projects representing over 250 ha of farmland were seeking financial and technical assistance to secure conservation easements and/or begin restoration planning (Alex Hackman, MassDER, personal communication). Limited financial resources and staffing for state and federal agencies that offer conservation easement and wetland restoration services currently prevents a broader and more rapid response. Our findings should motivate further public investment in acquiring conservation easements for flowthrough cranberry farms, and the planning, designing, permitting, and implementing of restoration projects.
In a survey given at the University of Massachusetts Amherst Cranberry Station Winter 2019 Meeting, 68% of grower respondents said they would only consider retirement and conservation given an easement payment of over $37,000 per hectare, while 90% of growers hypothetically required over $24,000 per hectare (n = 59; Hilary Sandler, personal communication). Current National Resource Conservation Service wetland easements typically offer between $22,000 and $33,000 per hectare in Massachusetts, while other interested parties, including commercial and solar developers, can easily outbid $33,000 per hectare. State and federal agencies should consider the economic landscape cranberry growers occupy and recognize that some sites, particularly flowthrough farms with the capability to become high-value wetlands, may be worth more investment.

Without the support of government funding agencies, growers looking toward farm retirement may have no other economically viable option other than selling to commercial developers. We recommend that funding agencies, restoration advocates, and the cranberry industry cooperate to help pair growers looking to exit the industry with organizations interested in easements and restoration.

Despite farmland retirement now occurring on a global scale, capitalizing on the opportunity this retirement presents for conservation and restoration requires application of local and regional knowledge. Industry-specific cultivation practices and local economic pressures uniquely influence the likelihood of retirement for different farmland. Cultivation practices as well as site-specific hydrology and soil conditions also influence the design, goals, and feasibility of ecological restoration projects in retired farmland. Remote imaging is just one tool for assessing the factors that influence farmland retirement and ecological restoration, but is especially relevant given the scale of farmland retirement now occurring worldwide and the impetus for regional restoration practitioners to capitalize on this opportunity for ecological restoration.

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