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RISK ASSESSMENT IN THE FACE OF A CHANGING ENVIRONMENT: GYPSY MOTH AND CLIMATE CHANGE IN UTAH

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Abstract. The importance of efficaciously assessing the risk for introduction and establishment of pest species is an increasingly important ecological and economic issue. Evaluation of climate is fundamental to determining the potential success of an introduced or invasive insect pest. However, evaluating climatic suitability poses substantial difficulties; climate can be measured and assessed in a bewildering array of ways. Some physiological filter, in essence a lens that focuses climate through the requirements and constraints of a potential pest introduction, is required. Difficulties in assessing climate suitability are further exacerbated by the effects of climate change.

Gypsy moth (*Lymantria dispar* L.) is an exotic, tree-defoliating insect that is frequently introduced into the western United States. In spite of an abundance of potential host species, these introductions have yet to result in established populations. The success of eradication efforts and the unsuccessful establishment of many detected and undetected introductions may be related to an inhospitable climate. Climatic suitability for gypsy moth in the western United States, however, is potentially improving, perhaps rapidly, due to a general warming trend that began in the mid 1970s and continues today. In this work, we describe the application of a physiologically based climate suitability model for evaluating risk of gypsy moth establishment on a landscape level.

Development of this risk assessment system first required amassing databases that integrated the gypsy moth climatic assessment model, with host species distributions, and climate (historical, present, and future). This integrated system was then used to evaluate climate change scenarios for native host species in Utah, with the result that risk of establishment will dramatically increase during the remainder of the 21st century under reasonable climate change scenarios. We then applied the risk assessment system to several case histories of detected gypsy moth introductions in Utah. These applications demonstrated the general utility of the system for predicting risk of establishment and for designing improved risk detection strategies.

Key words: aspen; climate change; climatic suitability; exotic pests; global warming; gypsy moth; introduced species; Lymantria dispar; *maple; oak; risk assessment.*

Introduction

Evaluating the impacts of climate warming on exotic species requires addressing a suite of questions pertaining to the probabilities of both introduction and subsequent establishment. Of these questions, three are basic to formulating an appropriate management response to introduction of any exotic species: (1) Will an introduction of the pest be damaging? (2) What is the likelihood of the pest being introduced? (3) What is the probability of successful establishment after an introduction?

In this paper, we explore these three general issues for the specific case of gypsy moth (*Lymantria dispar* L.) introductions in Utah, USA. In particular, we focus on the third of these questions. Although we specifically consider Utah, the approaches we develop are applicable to a much wider geographic range and are not restricted to any particular exotic introduction.

Experience with gypsy moth introductions indicates that where it has become successfully established, it became a serious defoliator, particularly along the leading edge of colonization (Sharov and Liebhold 1998). This evidence leads to the conclusion that gypsy moth is capable of inflicting serious damage to native hosts in the Rocky Mountain West, primarily aspen, oaks, and maples. Aspen is of particular interest in view of the widespread concern regarding range loss and decline of this critically important species (see Rogers [2002] for a good review). Thus, gypsy moth is a potentially threatening exotic insect to western U.S. forest ecosystems.

Multiple detections of gypsy moth introductions occur every summer throughout the western USA.

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Gypsy moth females are indiscriminant in their choice of oviposition sites, including vehicles and other items frequently transported in human activities. This behavioral characteristic, combined with the high influx of immigrants and tourists from areas where the insect is well established, virtually insures future introductions of this pest into the western USA. In fact, gypsy moths are introduced many times each year at various places in the interior west during times when populations could conceivably become established. These introductions included the serious Utah events of 1988–1993, and 1997–1999, when established populations were detected (and subsequently eradicated) in the area of Salt Lake City, Utah. The likelihood of future introductions, therefore, is a virtual certainty.

Answering the final question, determining probability of establishment after introduction, is more problematic than the former two. Determining whether an introduction will lead to the development of a persistent population (establishment) is difficult because the answer involves complex ecological interactions. In view of the many documented (and an unknown number of undetected) introductions that have either been successfully eradicated, or have naturally failed to become established, it seems likely that under current climatic conditions many native habitats in the interior west are only marginally suited for gypsy moths. How this assessment could change under climate change scenarios is largely an unanswered question.

The specific answers to the three general questions for establishment of an exotic introduction results in an interesting risk assessment situation. (Note that the inconsistent use of the terms "risk" and "hazard" has led to confusion in the pest management literature. For the sake of consistency, we will use "hazard" when referring to suitable climate and "risk" for the joint occurrence of suitable climate and presence of host plants.) Gypsy moth is a potentially serious pest, but the actual risk posed by an introduction may or may not warrant an aggressive response. We evaluated risk for establishment of a detected introduction by combining a hazard analysis developed by Régnière and Nealis (2002) with additional data layers that are specific to Utah. Combining these spatial data layers in a geographic information system (GIS) resulted in a risk assessment for establishment of detected gypsy moth introductions. In application of this risk assessment, we first identified the National Climate Data Center (NCDC) Divisions in Utah that contain native hosts. An analysis of historic temperature trends in the identified NCDC Divisions was then performed. We next analyzed the temporal trend of gypsy moth establishment hazard along a north–south transect across the state, and compared these results with the empirical analysis of NCDC climate data. State-wide hazard maps were then produced and combined with host distributions to evaluate the risk of gypsy moth establishment for historical and projected future climate. Finally, we illustrated applications for risk assessment of gypsy moth introductions detected during the summers of 2003 and 2004.

Methods

Required databases

Digital elevation models.—The basic geographic representation we used were digital elevation models (DEMs) of appropriate scale, depending on the specific application. We obtained all required U.S. Geological Survey DEMs from an appropriate Internet data gateway. These data were merged and converted into the most useable format compatible with ArcMap GIS software.

Weather/Climate.—Historical weather data (daily minimum and maximum air temperature records) were obtained from the National Climate Data Center (NCDC) Summary of the Day database for the period 1895–2003. In addition to individual weather stations, we used NCDC Climatic Division summaries for analysis of historical climate trends and for comparison to projected climate change scenarios.

Future climate was obtained from the output of two widely used General Circulation Models (GCMs): the CGCM1 model developed by the Canadian Centre for Climate Modeling and Analysis and the Hadley Centre for Climate Prediction and Research HADCM2SUL model (both models *available online*).[6,7] Both of these are transient models; i.e., if CO_2 levels were held constant at any point in time, temperature would continue to increase until equilibrium was reached. Comparisons between these two models for the Rocky Mountain/Great Basin region indicated no clear advantage of one over the other for reproducing historical weather patterns (Mearns 2003*a*). We used the CGMC1 model for our analyses, although projections from both GCMs are available in the databases we developed.

A generally recognized problem with application of GCMs is the finest scale used for global climate simulation is too coarse for meaningful ecological applications. This problem has been addressed through modeling and interpolation techniques that project GCM predictions to ecologically meaningful spatial and temporal scales. An example is the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP; *available online*)[8] (Kittel et al. 1995) that has produced a database of daily temperature (maximum and minimum) and precipitation at a 0.5 arc degree resolution grid for the conterminous United States over the period 1895–2100. Briefly, the VEMAP procedure used historical NCDC data (dating to 1893) and high elevation SNOTEL sites (dating from the 1970s) to interpolate weather records. The interpolation rules derived from

6, ⟨http://www.cccma.bc.ec.gc.ca⟩
7 ⟨http://www.met-office.gov.uk/research/hadleycentre⟩
8 ⟨http://www.cgd.ucar.edu/vemap⟩

TABLE 1. Utah National Climate Data Center (NCDC) climate statistics (temperatures, in °C) for VEMAP climate change scenarios, CGMC1 model. Temperatures are averages over the 30-year normal period indicated.

Temperature statistic	Zone number 1	2	3	4	5	6	7
1961–1990							
Minimum	0.97	6.86	2.28	0.33	–1.27	–0.85	3.01
Mean	9.48	15.15	9.49	8.78	6.74	7.7	10.9
Maximum	17.99	23.43	16.7	17.23	14.76	16.26	18.8
1971–2000							
Minimum	1.1	7.25	2.86	0.61	–1.36	–0.51	3.67
Mean	9.62	15.66	9.94	8.94	6.52	7.98	11.42
Maximum	18.15	24.08	17.02	17.28	14.4	16.47	19.18
1981–2010							
Minimum	1.78	5.98	1.46	0.48	–2.45	–0.07	3.49
Mean	9.68	13.83	8.81	8.53	5.09	8.12	11.24
Maximum	17.59	21.68	16.15	16.58	12.64	16.31	18.98
1991–2020							
Minimum	2.3	6.31	1.92	0.95	–1.98	0.38	3.97
Mean	10.19	14.2	9.3	8.99	5.59	8.57	11.67
Maximum	18.09	22.09	16.69	17.03	13.15	16.76	19.36
2001–2030							
Minimum	2.82	6.74	2.43	1.43	–1.50	0.86	4.4
Mean	10.64	14.59	9.76	9.42	6.03	9.04	12.08
Maximum	18.45	22.44	17.08	17.41	13.56	17.21	19.76
2011–2040							
Minimum	3.46	7.26	3.13	2.05	–0.78	1.58	5.01
Mean	11.2	15.07	10.35	9.93	6.62	9.61	12.58
Maximum	18.93	22.87	17.57	17.82	14.02	17.62	20.14
2021–2050							
Minimum	4.08	7.71	3.85	2.5	–0.07	2.22	5.51
Mean	11.65	15.36	10.92	10.3	7.2	10.15	13.03
Maximum	19.22	23.01	17.99	18.06	14.47	18.07	20.55
2031–2060							
Minimum	4.73	8.22	4.58	3.13	0.68	2.93	6.11
Mean	12.16	15.73	11.47	10.72	7.76	10.65	13.45
Maximum	19.58	23.24	18.36	18.31	14.84	18.37	20.8
2041–2070							
Minimum	5.44	8.77	5.39	3.77	1.49	3.7	6.77
Mean	12.64	16.07	12.07	11.16	8.36	11.26	13.98
Maximum	19.85	23.36	18.74	18.54	15.24	18.83	21.19
2051–2080							
Minimum	6.09	9.31	6.13	4.44	2.28	4.51	7.48
Mean	13.14	16.48	12.64	11.65	8.98	11.89	14.53
Maximum	20.2	23.64	19.15	18.85	15.69	19.27	21.57
2061–2090							
Minimum	6.86	9.94	6.99	5.15	3.16	5.37	8.19
Mean	13.78	16.99	13.38	12.22	9.75	12.64	15.14
Maximum	20.71	24.05	19.77	19.29	16.33	19.91	22.09
2070–2100							
Minimum	7.45	10.46	7.67	5.68	3.83	5.99	8.72
Mean	14.32	17.43	14	12.71	10.38	13.27	15.71
Maximum	21.18	24.4	20.32	19.74	16.93	20.54	22.69

the historical analysis were then used to project (downscale) GCM-predicted climate change weather to the higher spatial resolution.

Weather from 1990–2100 was simulated in the VEMAP project by assuming a 1% per year increase in CO_2-equivalent green house gases (Table 1). An annual increase of 1% results in a CO_2 doubling in ~70 years or by 2060. This rate compares to the International Panel on Climate Change estimate of CO_2 doubling by 2030 under a "business-as-usual" scenario (IPCC 1990). From these data, 30-year normals (mean monthly minimum and maximum, extreme monthly minimum and maximum, and variance of the monthly mean air temperature) can be computed for any selected interval during 1900–2100. These predicted normals were used as the climate database for computing establishment hazard (both for historical and projected periods).

Vegetation maps.—The two primary native host species for gypsy moth that occur in Utah are aspen (*Populus tremuloides* Michx.) and oaks (predominately Gamble's oak, *Quercus gambelii* Nutt.). Maples (predominantly big tooth maple, *Acer grandidentatum* Nutt.) are a moderately preferred host species. Gypsy moth caterpillars feed on >500 plant species (Liebhold et al. 1995), but they are tannin-adapted insects (Barbosa and Krischik 1987) and preferentially feed on oaks, *Quercus* spp. (Foss and Rieske 2003). The larvae favor the leaves of deciduous hardwood trees, such as elm, oak, and aspen (Forbush and Fernald 1896, Mosher 1915, Miller and Hanson 1989). No gypsy moth feeding studies have been conducted using gamble oak or big-tooth maple. However, Montgomery and Wallner (1988) listed host plant preferences of the gypsy moth based on laboratory and field observations that document that oak (*Quercus* spp.) and aspen (*Populus* spp.) are preferred hosts and that some species of maple (*Acer* spp.) are moderately preferred hosts of the gypsy moth.

Digitized maps for these three forest cover types were obtained from the Utah 30-m resolution GAP Analysis Program data (Edwards et al. 1995). Although the distributions of these native host species will undoubtedly change in response to global warming, the response time of hosts (decades) is much longer than that of introduced gypsy moths (one year). It is, therefore, valid to model gypsy moth risk as a fast variable assuming the slow variable of host distribution is constant (Ludwig et al. 1978).

Land use and ancillary data.—These data were acquired from appropriate data gateways and were used to facilitate interpretation of hazard and risk maps.

Gypsy moth phenology model

A composite temperature-driven model of gypsy moth phenology assembled by Régnière and Sharov (1998) and modified by Régnière and Nealis (2002) was used to simulate the gypsy moth's response to particular annual cycles of daily air temperatures. In this composite model, the three-phase (prediapause, diapause, and postdiapause) model developed by Gray et al. (1991, 1995, 2001) was used to simulate the time from oviposition in late summer to hatch the following spring. Larval development was simulated using the model of Logan et al. (1991), and pupal development was simulated by data in Sheehan (1992). Finally, adult longevity was represented by the relationship in Régnière and Sharov (1998). The model time step is four hours, with temperatures interpolated by half sine curves between successive daily minimum and maximum values. Due to the importance of thermal regimes in gypsy moth ecology and management, this physiologically based model has been widely applied (Régnière and Sharov 1997, 1998, 1999, Régnière and Nealis 2002, Gray 2004).

Application of the model for hazard evaluation involved assessing model prediction of an adaptive seasonality. The phenological basis for an adaptive seasonality was described by Logan and Powell (2004) as follows: "Critical life-history events must be keyed to appropriate seasonal cycles in order to avoid lethal temperatures or other environmental extremes, provide for coincident timing of reproductive cycles, avoid predation through simultaneous mass emergence, and a multitude of other requirements for maintaining ecological and biological viability." Subsequent establishment of a gypsy moth introduction requires maintaining phenological integrity at the site of introduction. This requirement is conservative; model prediction of an appropriate seasonality does not necessarily indicate establishment will occur, but lack of an adaptive seasonality almost certainly implies that subsequent establishment will not occur.

Motivated by the basic gypsy moth life cycle, an appropriate seasonality can be evaluated based on a single criterion: that median adult emergence occurs early enough in the year to find a mate, oviposit, and for eggs to subsequently complete prediapause development before the onset of winter (Régnière and Nealis 2002). Failure to meet this criterion can happen for three reasons: (1) inadequate heat in late summer for eggs to complete prediapause development before the onset of winter; (2) insufficient chilling temperatures to complete diapause during winter; and (3) inadequate summer heat to complete the remaining life stages (postdiapause egg, larval, and pupal development) until oviposition.

Preliminary model simulations using 2071–2100 temperature normals indicated that winter chilling conditions required to complete diapause development will be met everywhere in Utah, even with the most severe climate warming scenarios we considered. Using current (1971–2000 normals) temperatures, we determined that lack of sufficient heat to complete prediapause egg development occurred only at elevations exceeding ~2700 m and that lack of sufficient summer heat to complete the life cycle from egg hatch to oviposition also occurred only at higher elevations, but below the previous result, i.e., ~2000 m. Therefore, checking model results for one condition, date of median oviposition, is sufficient for determining if the criterion for adaptive seasonality is met.

The model was initiated at an arbitrary (but reasonable) oviposition date (ordinal date (OD) 190 = 9 July), and allowed to run for 10 generations. Preliminary simulation work indicated that model output was not influenced by this initial condition, within reasonable limits (summertime oviposition). In each new generation t, the oviposition date was reset to the date of median adult female emergence in the previous generation $t - 1$. If the population persisted for 10 generations without violating the viability criterion, the evaluated annual temperature cycle was determined to be adaptive (establishment flag, $F = 1$); if not, then it was determined to be maladaptive (establishment flag, $F = 0$). The first part of October (OD275) was chosen as the threshold date after which it is unlikely that eggs in Utah would receive enough thermal energy to enter diapause. However, conclusions reached with the model were not sensitive to this date. Results from previous work (Powell and Logan 2005) have indicated rapid convergence (at least exponentially fast) to a stable oviposition date if a steady state exists. This result is true even for systems without diapause; the existence of diapause further stabilizes the system, resulting in very little transience in such models. Absence of a steady state would, therefore, result in rapid violation of the OD275 rule, and 10 generations is more than sufficient for evaluation.

Landscape projection of gypsy moth establishment hazard

Implementation of the gypsy moth phenology model in the BioSIM system was used to obtain landscape maps of gypsy moth establishment hazard. The BioSIM system (Régnière 1996) is based on a sampling paradigm that runs the gypsy moth phenology model for each location sampled from a DEM (typically we found 500 locations to be adequate), and then interpolates these sampled points to result in a continuous map of establishment hazard. This was accomplished by: (1) Weather-related driving variables were interpolated (Régnière and Bolstad 1994) from the VEMAP grid data for each sampled location, and these data were used to run the model. (2) The model was run for 10 consecutive generations with the generated weather data, and an establishment flag (F_i) was computed. (3) Steps (1) and (2) were replicated 50 times for each sampled location. (4) A probability for adaptive seasonality (establishment hazard) was computed for each location (see Eq. 3). (5) The resulting establishment probabilities were then used in an interpolation algorithm (kriging) to produce a data layer of gypsy moth establishment hazard. Output was a GIS data layer that can be combined with other georeferenced data to produce maps of establishment risk (refer to Figs. 6, 8, 9, and 11). The specific algorithms used are described below.

Weather interpolation.—Adequate interpolation of weather data is the basis for reliable phenology model output (Jarvis et al. 2003). Daily minimum and maximum air temperature inputs were generated by BioSIM in the following manner. First, 30-year normals from the nearest sources of weather data (either NCDC Summary of the Day stations or VEMAP gridded locations) were interpolated by the gradients with inverse-distance-squared (GIDS) weighting technique (Nalder and Wein 1998). The GIDS approach uses multiple linear regression fitted to data from a number of the nearest sources of weather data:

$$Y = a + m_E E + m_N N + m_W W \tag{1}$$

where Y is observed climate value (e.g., mean monthly minimum air temperature), E is elevation, N is latitude, and W is longitude of the region's weather stations; a is an intercept constant, and m_E, m_N, and m_W are regional thermal gradients for elevation, latitude, and longitude, respectively. These gradients were applied to differences in latitude (ΔN), longitude (ΔW), and elevation (ΔE) between a small number (we used four) of the nearest sources of weather data and the simulation point, and an inverse-distance-squared ($1/d^2$) weighted average estimate of the ($\hat{Y}$) datum was calculated:

$$\hat{Y} = \frac{\sum_{i=1}^{4}\left[\frac{1}{d_i^2}(Y_i + m_E \Delta E_i + m_N \Delta N_i + m_W \Delta W_i)\right]}{\sum_{i=1}^{4}\frac{1}{d_i^2}}. \tag{2}$$

It was important to provide realistic daily temperatures, since the composite phenology model included nonlinear thermal response functions (Logan et al. 1976, Régnière and Logan 2003). Several daily weather generators have been developed (Richardson 1981, Richardson and Wright 1984, Racsko et al. 1991, Hutchinson 1995, Wilks 1999), but these often require calibration and a considerable quantity of input information for application in specific geographical areas. Régnière and Bolstad (1994) developed a generally applicable algorithm (TempGen) for simulation of daily minimum and maximum air temperature using monthly normals. This method was modified to include annual variation of monthly mean temperature (J. Régnière, *unpublished manuscript*), as interannual weather variation can have considerable impact on calculations of establishment probabilities (Jarvis and Baker 2001*a*, *b*). We used the modified Régnière and Bolstad algorithm in BioSIM to produce daily max/min temperature values for all simulations.

Hazard Evaluation.—Probability of establishment maps were obtained by randomly sampling 500 locations (latitude and longitude) over the area covered by a DEM of appropriate scale (e.g., ranging from 1:250 000 [90 m] for the state of Utah to 1:24 000 [10 m] for individual trap analysis). The elevation for each sampled point was determined from the DEM, and 50 annual series of daily minimum and maximum air temperatures were stochastically generated using the TempGen algorithm based on 30-year normal statistics for each point. The probability of establishment (p) at each point was then computed as the average of the 50 output establishment flags (F_i):

$$p = \frac{1}{50}\sum_{i=1}^{50} F_i \tag{3}$$

where i is the replicate index.

Output interpolation.—Spatial interpolation of model outputs (500 p values) was accomplished by universal kriging with elevation as external drift (Deutsch and

Journel 1992, Régnière and Sharov 1999, Gignac 2000) to generate output maps of establishment probabilities at the same spatial resolution as the input DEM. The kriging algorithm's search radius was set to 500 km, with 10 and 40 as the minimum and maximum number of neighborhood points for interpolation. Other kriging parameters, such as lag distance, number of lags, and variogram model were optimized by automatic iteration on the basis of the coefficient of determination obtained by a jackknife (remove and estimate) cross validation procedure. To linearize p values before kriging, the logistic transformation was used:

$$g(p') = \ln\left(\frac{p'}{1+p'}\right) \quad (4)$$

where $p' = [(np+1)/(n+2)]$ and $n = 50$ (replicates). After kriging, the interpolated surfaces were back-transformed to probabilities (so that final maps are within the [0, 1] probability range).

The final BioSIM-produced kriged map resulted in a gypsy moth establishment hazard GIS layer.

Analysis of historical weather in Utah

Empirical evidence indicates an accelerated warming trend across the western United States that began in the late 1970s to early 1980s and continues to present (K. Redmond, *personal communication*). This increasing trend was modeled by fitting a piecewise-linear regression to data from NCDC Utah, Divisions 4 and 5. The model used was as follows:

$$y = \beta_1 + \beta_2 x + \beta_3(x - \beta_4\text{: } x \geq \beta_4\text{; zero otherwise}) \quad (5)$$

where β_1 is the intercept, β_2 is the slope of the trend line prior to the break point β_4 (the date at which time the slope changes), and $\beta_2 + \beta_3$ is the slope of the linear trend line following the break point. Eq. 5 was fitted by nonlinear least-squares regression to Lowess-smoothed (with 30-year moving window) NCDC mean annual temperatures.

North–south gradient of hazard evaluation in Utah

A series of 101 simulation points was located evenly across the north–south axis of Utah between 37° N, 112° W and 41° N, 111° W (Fig. 1). For each point, input for the model consisted of observed daily minimum and maximum air temperature data for each year between 1971 and 2003 (NCDC Summary of the Day data). Temperature data were interpolated from the two recording stations nearest to each simulation point by the GIDS method, with thermal gradients in Eq. 1 estimated from monthly normals of the 1971–2000 period (using the 20 nearest stations). Because these simulations were based on actual weather records, simulations did not need to be replicated. The relationship between the establishment flag F output by the phenology model, year (Y), elevation (E), and latitude (N) was determined by binary logistic regression using two models:

$$g(F) = a + b_Y + cN + dE + \varepsilon \quad (6)$$

$$g(F) = a + bY + cN + dE + \varepsilon \quad (7)$$

where $g(F)$ is the logistic link function of F; ε is a binomially distributed error term; and a, b or b_Y, c, and d are regression parameters. In Eq. 6, Y was used as a factor (categorical variable) and thus b_Y is an array of intercept parameters providing a distinct equation for each year (with common slopes for latitude and elevation). In Eq. 7, Y was used as a covariate (regression variable), so that parameter b tested for a time trend. By rearranging these models, the elevation $E_{0.5}$ at which the probability of establishment drops below 0.5 can be calculated as

$$E_{0.5} = -\frac{(a + b_Y + cN)}{d} \text{ or } \frac{(a + bY + cN)}{d}. \quad (8)$$

Results

Analysis of historical weather in Utah

The total area currently occupied by the gypsy moth's two primary host plants in Utah is 8696 km^2 for aspen, and 6724 km^2 for oak. Maple occupies a much smaller area of ~636 km^2. The majority of these forest cover types are contained in NCDC Utah Climate Divisions 4 and 5: 86.4% for aspen, 61.3% for oak, and 78.8% for maple (Fig. 1, Table 2). Our climate analysis, therefore, closely followed Baldwin (2003), where his West Central Rockies (WCR) subregion (Baldwin 2003: Fig. 3.18) contains most of NCDC Utah Climate Divisions 4 and 5.

Eq. 5 was fitted by nonlinear least-squares regression to the Lowess-smoothed NCDC mean annual temperatures. The results of this analysis (Fig. 2, Table 3) indicate a slowly increasing trend from 1895 until $\beta_4 =$ 1983, followed by a much steeper increase. The post-1983 slope ($\beta_2 + \beta_3$) of mean annual temperature is an order of magnitude greater than that of the pre-1983 period: the estimated value of β_2 (Table 3) predicts 0.54°C warming over the period 1895–1983, while $\beta_2 + \beta_3$ yields a 0.86°C increase in mean annual temperature over the period 1983–2002.

North–south establishment hazard transect in Utah

Logistic regression (Eq. 6) accurately described the relationship between predicted gypsy moth establishment hazard, latitude, and elevation along the north–south transect (Fig. 1) in Utah (concordance between model output F values and predicted probabilities exceeded 99% in all years). Examples of probability surfaces for 1983 (a cold year) and 2003 (a warm year) are illustrated in Fig. 3. The model in Eq. 7 also fitted the data quite well (99.4% concordance), with all regression terms highly significant ($b = 0.072 \pm 0.012$, $P < 0.001$; $c = -2.26 \pm 0.18$, $P < 0.001$; $d = -0.016 \pm$

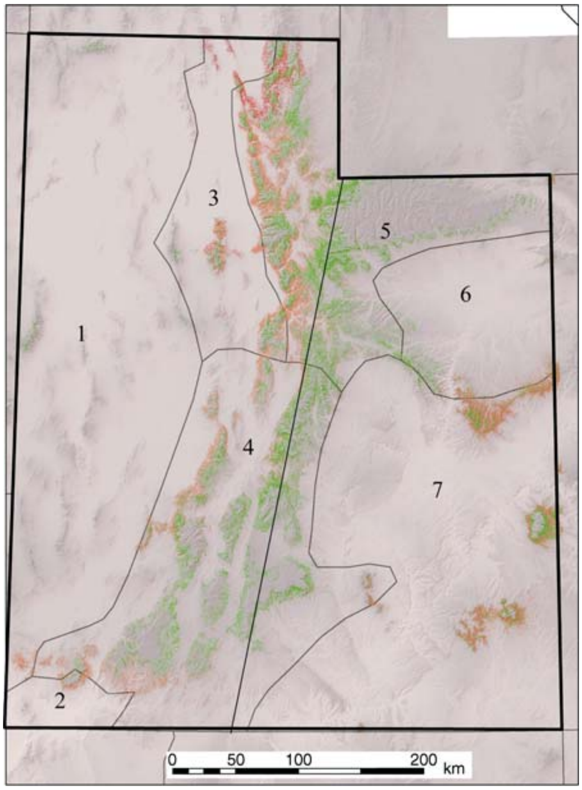

FIG. 1. The distribution of aspen (green), oak (orange), and maple (red) in Utah (GAP data), also showing the boundaries of the seven National Climate Data Center (NCDC) Climate Divisions for Utah. The black off-vertical line across the state is the transect position used for the north–south gradient of establishment probability simulations.

0.001, $P < 0.001$; the value of each regression parameter appears as mean ± SE). As expected, the probability of gypsy moth establishment dropped with increasing elevation and northern latitude (indicating colder climates). The positive slope b of the relationship with time in Eq. 7 indicates that over the period 1971–2003 gypsy moth establishment hazard across Utah has increased.

The value $E_{0.5}$ calculated with Eq. 8 (elevation at which the probability of gypsy moth establishment dropped below 0.5) fluctuated considerably from year to year, but increased over time, especially after the mid 1980s (Fig. 4). The results of this analysis closely reflect those obtained in the empirical climate analysis.

Gypsy moth establishment risk analysis

The statewide risk (proportion of the area covered by each host plant group overlapping with $p \geq 0.5$ gypsy moth establishment) increased considerably from the beginning of the 20th century to the end of the 21st (Fig. 5). The preclimate change (prior to 1961) proportion of aspen cover type at high risk hovered at ~10%, and most of this was at the fringe (noncontiguous) of the plant's distribution in Utah (Fig. 6A). A gradual increase in area followed during the next two decades so that by 1991 the area at risk reached 33% (Fig. 6B). At the end of the series in 2071 the amount of aspen cover type at high risk for gypsy moth establishment increased to 93% (Fig. 6C). Both maple and oak had a relatively high proportion of their distribution at high risk of establishment in preclimate change conditions (38% and 69%, respectively) and both reached 100% at high risk by 2071 (Fig. 5). The temporal trends of risk to all three host plants, especially aspen, correspond well to that of observed climate (Fig. 2) and are consistent with our model predictions for gypsy moth establishment hazard (Fig. 4).

EXAMPLE APPLICATIONS

The risk assessment system we developed is independent of spatial scale, i.e., it can be used for production of statewide maps as well as more localized analysis for a particular detected introduction. Example applications of this system are provided for (1) assessing the impact of climate change impacts for an introduction that was detected during the summer of 2003, and (2) risk analysis for three detected gypsy moth introductions that occurred during the summer of 2004.

Lyman Lakes trap recovery: summer 2003

The Rainbow Family of Living Light held their 2003 summer gathering in the Uinta Mountains of Northern Utah. Although the main celebration occurred on 4 July, the site was occupied by a large number of people (9000–12 000, depending on information source) for several weeks before and after this date. Thus, the components

TABLE 2. Utah NCDC Climate Divisions with the coverage of native gypsy moth host plants in each Division.

Division	Percentage of host in Division			Percentage of Division covered by host		
	Aspen	Oak	Maple	Aspen	Oak	Maple
1	1.2	1.8	1.1	0.2	0.2	0.01
2	0.2	1.3	0.09	0.4	2.4	0.02
3	2.8	7.5	20	1.7	3.4	0.85
4	40.4	26	0.3	8.1	4.0	0.0
5	46.0	35.3	78.5	13.4	7.9	1.7
6	2.6	3.4	0.0	1.5	1.6	0.0
7	6.8	24.8	0.0	1.1	3.1	0.0

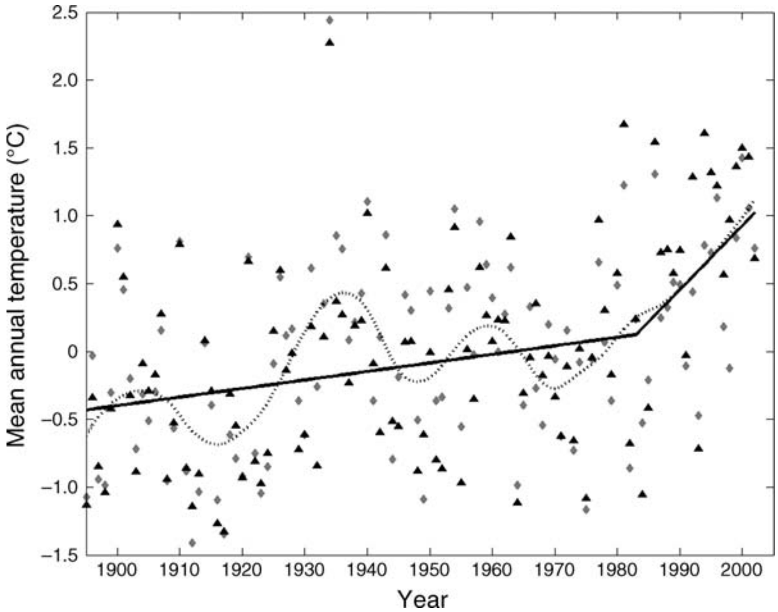

FIG. 2. Deviation (temperature, °C) from mean annual temperature for Utah NCDC Division 4 (diamonds) and Division 5 (triangles), with fitted Lowess-estimated trend line (dotted line), and piecewise linear model (solid line; Eq. 5).

were present for a gypsy moth introduction: numerous visitors, many from within the established distribution of gypsy moth, and visitations over the time when pupal stages can be transported and emerging adult moths introduced onto the landscape.

Several gypsy moth detection traps were deployed in the vicinity of the gathering in June of 2003. Detection traps were collected in the fall, and two adult male gypsy moths were recovered. The most likely source for these moths was introduced gypsy moth pupae transported into the area by summer visitors. In response to this detection, the Utah Department of Agriculture proposed an ambitious delimiting trap-monitoring program involving placement of several hundred traps on a 304.8-m grid near the site of the original captures. This action was undertaken during the summer of 2004 with no adult moths trapped. The risk assessment question becomes this: Was this level of concern warranted, and was the subsequent expense justified?

Simulations with current climate (1981–2010 normals) indicate that it is highly unlikely that gypsy moth could become established at this high elevation site. In fact, our simulations indicate that the nearest vulnerable aspen were almost 48.3 km away downwind (east) and 40.2 km upwind (west) from the trap recovery location, where vulnerability is defined as >50% probability of establishment (i.e., $p \geq 0.5$) (Fig. 7). Simulations based on 2041–2070 normals indicated that some of the area in the Lyman Lakes quadrangle will become high risk by that time, providing a possible conduit to areas of contiguous aspen. By 2071–2100, most aspen in the area is projected to be at high risk for successful gypsy moth establishment (Fig. 8).

Considering these results, there is little reason to be concerned about the two gypsy moths that were trapped in the Lyman Lakes area. A better use of resources would have been to place a few traps near the point of recovery and focus available resources on increased monitoring in popular, high-visitation areas that are also identified as having a high probability of establishment for introduced gypsy moths.

Had this system been available to resource managers in the summer of 2003, the expense of an aggressive monitoring effort of summer 2004 could have been avoided. However, the probability of establishment, and therefore risk, is predicted to rapidly increase over the 21st century as a result of climate warming. Risk assessment, therefore, needs to be a dynamic process geared toward evaluating a potentially improving thermal habitat for gypsy moth establishment in the critical aspen zone. Updating climate analysis based on historical and current weather data and resulting risk predictions on a five-year interval seems reasonable.

TABLE 3. Utah NCDC pooled Division 4 and 5 parameters fitted to Lowess-smoothed data.

Parameter	Estimate	L 95% CL	U 95% CL
β_1 pre-CC intercept	−12.37	−15.15	−9.95
β_2 pre-CC slope	0.0063	0.0049	0.0077
β_3 post-CC additional slope	0.041	0.028	0.055
β_4 break point	1983	1979	1987

Notes: CC indicates climate change, L 95% CL is the lower 95% confidence limit, U 95% CL is the upper 95% confidence limit, and β_i are the parameters designated in Eq. 5.

Risk analysis: summer 2004

During the summer of 2004, three gypsy moth introductions were detected, each by recovery of a single male moth in detection traps. The three trap sites were located in urban Salt Lake City, an urban–wildland interface community in Summit County near Park City (a large ski/resort community), and a high-elevation wildland site in the Uinta Mountains. These three sites have distinctly different risk criteria. Five hazard categories are identified on each map in Figs. 9 and 11: (1) $p < 0.2$ (green), (2) $0.2 \leq p < 0.4$ (yellow), (3) $0.4 \leq p < 0.6$ (tan), (4) $0.6 \leq p < 0.8$ (orange), (5) $0.8 \leq p < 1.0$ (red). The climate base for all maps were normal temperatures computed for the period 1980–2010.

The Salt Lake City trap recovery occurred in a residential zone in the northeast part of the city. This recovery is embedded deep within a red (highest) hazard zone (Fig. 9). Due to the abundance of suitable hosts (both native and ornamental) and the potentially high impact of gypsy moth in an urban setting, this introduction must be treated seriously. Further considerations include the proximity to native host species (oak) and the connectedness to the Summit County trap recovery site (through the corridor provided by gamble oak to aspen, Fig. 10).

One male moth was caught in a detection gypsy moth trap in Summit County. Although the establishment hazard was a lower category (orange) than the Salt Lake City recovery, the trapsite is very close to a susceptible host species, aspen (Fig. 10). The trapsite is in an area of urban–wildland development, and families with above-average expendable income typify the neighborhood. As a result, travel is common, and there tends to be a large number of visitors (proximity to the resort community of Park City) in both winter and summer, many from areas with established gypsy moth populations. The result is a high probability of continued introductions. Following the 2005 delimitation survey in this area, another male moth was captured near the 2004 positive trap catch site. The combination of socioeconomic and ecological circumstances indicates that this area should be actively monitored and that future trap recoveries are to be expected. Thus, an increasing trend in number of moths captured may or may not indicate establishment. However, with projected climate warming the thermal habitat of this area will improve in the near future, moving the hazard classification to the highest category. The same risk analysis in a wildland setting would lead to a different interpretation of subsequent trap recoveries. In a wildland setting, trap recoveries in successive years would be stronger inference for an established population because of a lower risk of repeated introductions.

The Mirror Lake trap recovery (one male) occurred near a popular campground (Mirror Lake) in the Uinta Mountains (Fig. 11). This was a low-risk introduction (green). There is little aspen in the area near the trap recovery, and the distance to the nearest contiguous aspen or other hosts is fairly large in all directions. In addition, prevailing winds (from the west) would disperse moths away from the nearest potential hosts. This area is at such low risk that follow-up is unnecessary.

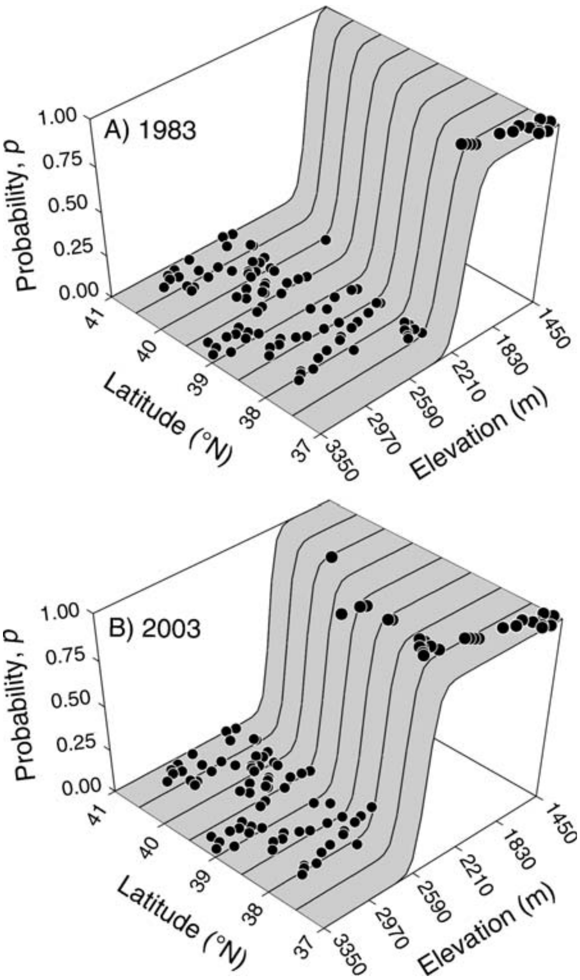

FIG. 3. Logistic relationship between probability of gypsy moth establishment (p), latitude, and elevation (based on NCDC Summary of the Day records along a north–south transect across Utah in (A) 1983 and (B) 2003. Individual climatic suitability flag values (F) appear as solid circles. Logistic regression surfaces are generated by Eq. 6.

The following summarizes the analysis of gypsy moth-monitoring trap catches from the summer of 2004: (1) The three recoveries occurred in very different ecological and socioeconomic settings. (2) The "appropriate" management response is situational dependent on the particular setting of the trap catch; that is, one size does not fit all. (3) The information provided by our risk assessment system is useful for both formulating an appropriate management response and for providing supporting evidence in documenting a potentially controversial decision to the public.

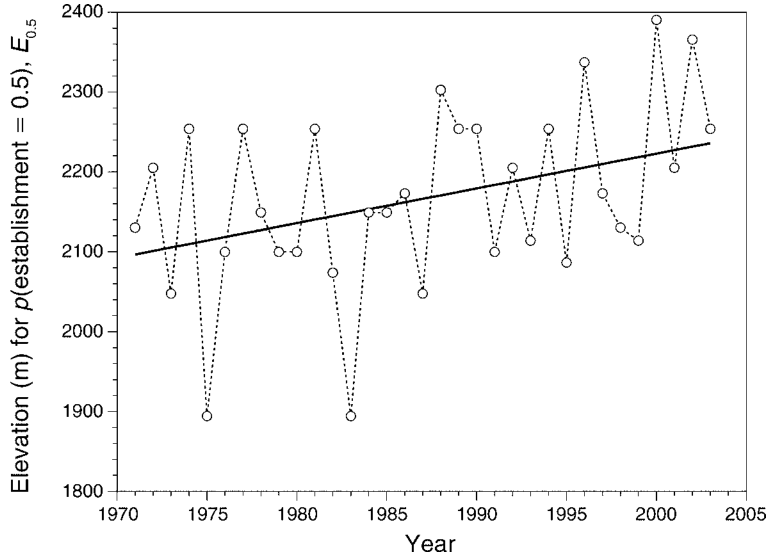

FIG. 4. Change through time of $E_{0.5}$, the elevation at which the probability of gypsy moth establishment (p) crosses 0.5, in the middle of the simulation transect across Utah (39° N, 111°30′ W), based on simulations using NCDC Summary of the Day records between 1971 and 2003. Open circles indicate results of the annual logistic regression model (Eq. 6); the solid line indicates results of the global logistic regression model (Eq. 7).

DISCUSSION AND CONCLUSIONS

While we recognize that the actual establishment (or failure) of an exotic introduction results from the complex interaction of a large number of factors not considered in this work, our results do indicate that we may be on the cusp of rapidly increasing risk, particularly to the aspen component, from gypsy moth introductions. Although direct validation of results we present is not possible (i.e., we describe the probability of future events, the occurrence of which has yet to happen), Logan et al. (2003) generated a map of gypsy moth establishment probability in North America under current weather conditions, based on the models and approach used here. Gray (2004) also mapped the climatic suitability of North America to gypsy moth using a similar methodology, with much the same results. The area currently occupied by the insect in the eastern Canada corresponds closely to Gray's results; compare Gray (2004: Fig. 6) with the Canadian Food Inspection Agency 2005 map for gypsy moth regulation (*available online*).[9] The gypsy moth is limited in this northern portion of its North American range by cold climate. It spread to the Canadian Maritimes in the 1930s, and to Quebec and Ontario in the later 1960s (Benoit and Lachance 1990, Nealis and Erb 1993).

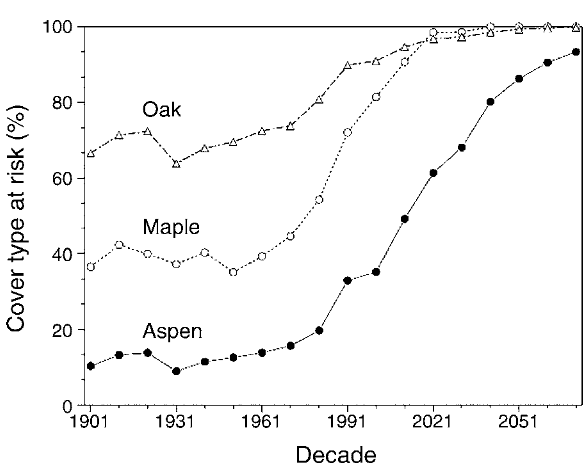

FIG. 5. Predicted change in risk (percentage of cover type with $p \geq 0.5$ of gypsy moth establishment) to aspen (solid circles), oaks (triangles), and maples (open circles) in Utah, based on normals from the 1901–1930 to 2071–2100 periods.

The implications of a long-term increasing trend in temperature, and perhaps spring precipitation, hold sufficiently serious consequences for risk of successful gypsy moth establishment in Utah that insightful monitoring is warranted. Aspen is of particular interest due to the high value of ecological services provided and because of the current concern for appropriate aspen management in the western United States (Shepperd et. al. 2001). Our analysis indicates that the thermal habitat was gradually improving for lower elevation oak and maple accompanying the gradual increase in temperatures prior to 1983 and, as of 2005, is beginning to be expressed in higher elevation aspen following the accelerated warming that has since occurred.

The question becomes, why has eradication of introduced gypsy moths been relatively easy to achieve in oak habitat where there is currently a high probability of establishment? The answer may lie in the differences

[9] ⟨http://www.inspection.gc.ca/english/sci/surv/2005maps/ldcanqz2005e.shtml⟩

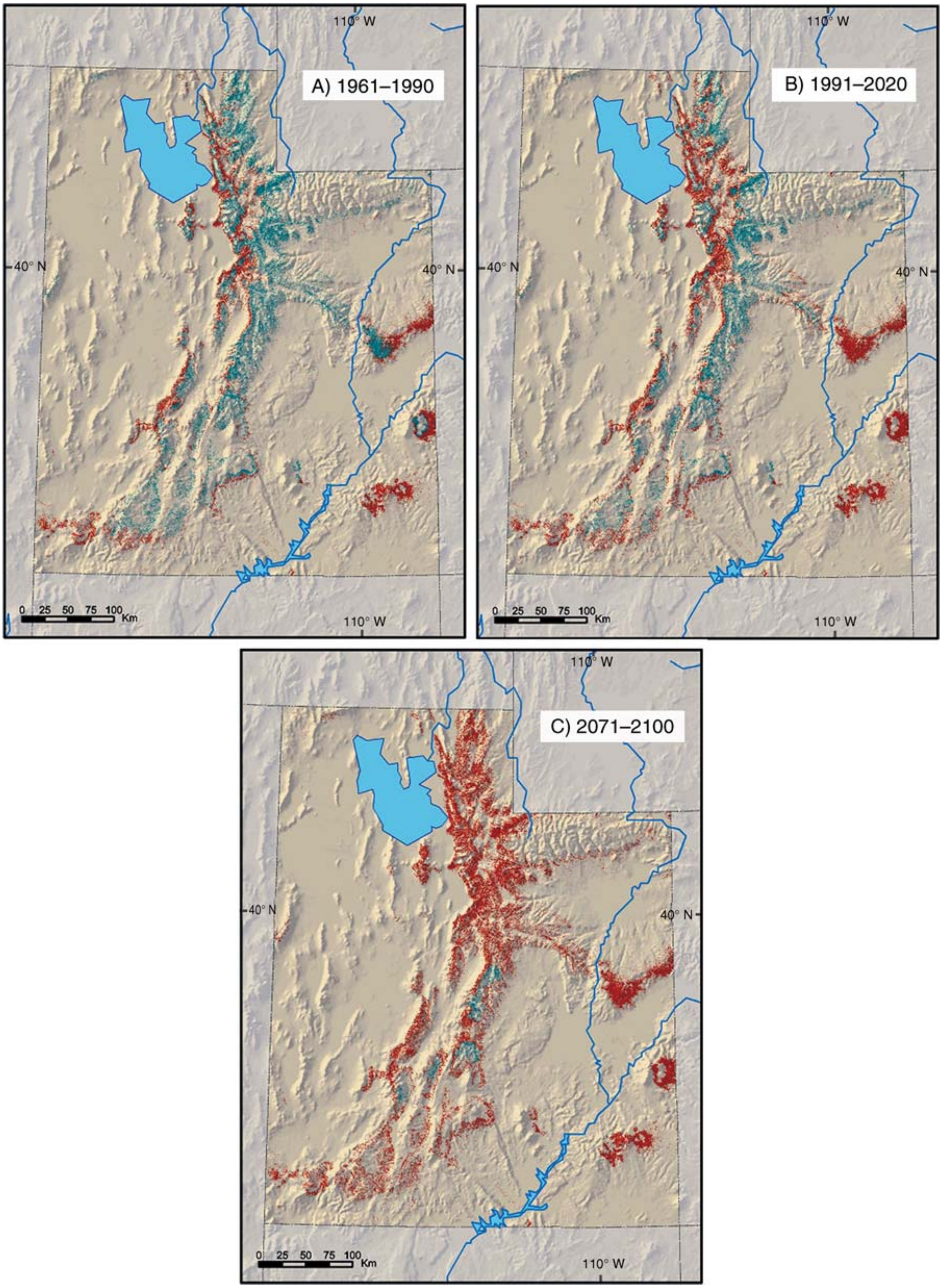

FIG. 6. Hazard maps ($p \leq 0.5$, green; $p > 0.5$, red) for the three primary host plants (aspen, oaks, and maples) in Utah, as effected by climate change: (A) 1961–1990 normals, (B) 1991–2020 normals, and (C) 2071–2100 normals (VEMAP gridded database).

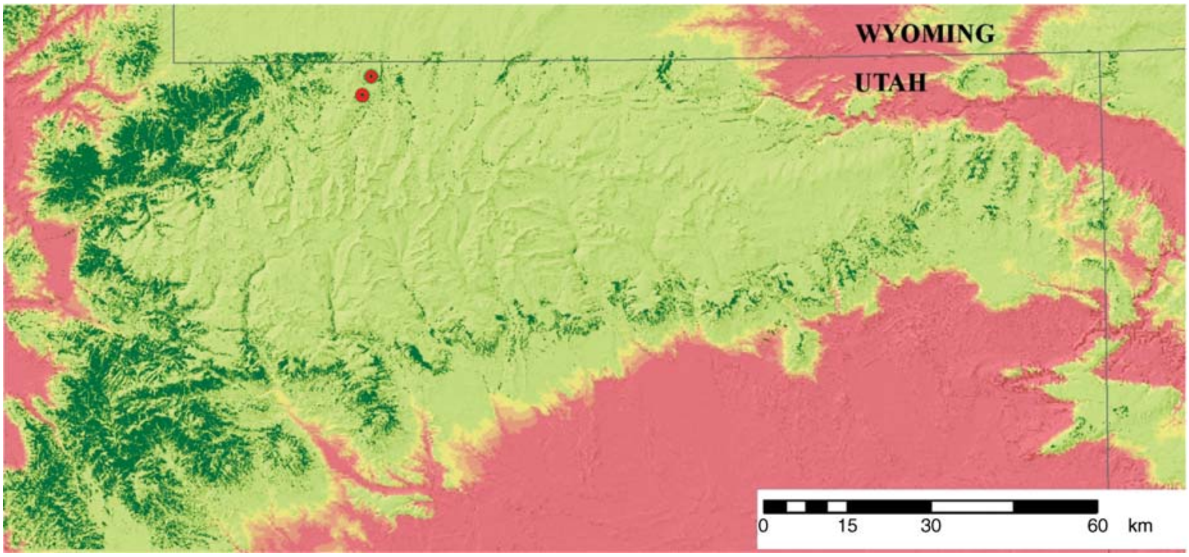

FIG. 7. Hazard rating for the Uinta Mountains of northern Utah is shown, ranging from green ($p = 0.0$–0.2) to red ($p = 0.9$–1.0), based on climate normals for 1981–2010. The locations for the 2003 trap recoveries are shown as red target-circles. Aspen distribution (Utah GAP data) is indicated by dark green.

in suitability to gypsy moth between oak and aspen habitats. Oak is typically found in relatively xeric situations (lower elevation, on southerly exposed slopes), while aspen is found on comparatively mesic sites; although exceptions to this generalization occur, particularly in urban–wildland interface zones along the Wasatch Front. At any rate, mortality of recently hatched gypsy moth larvae due to desiccation may be common in xeric habitats. We observed very low survival, with desiccated, young larvae remaining on the chorion, among sterile egg masses experimentally placed at several sites in southern Utah (J. Logan and A. Munson, *unpublished observations*).

Oak is of particular interest from the introduced-species perspective, not only due to the large area it covers in Utah, but also because its distribution is

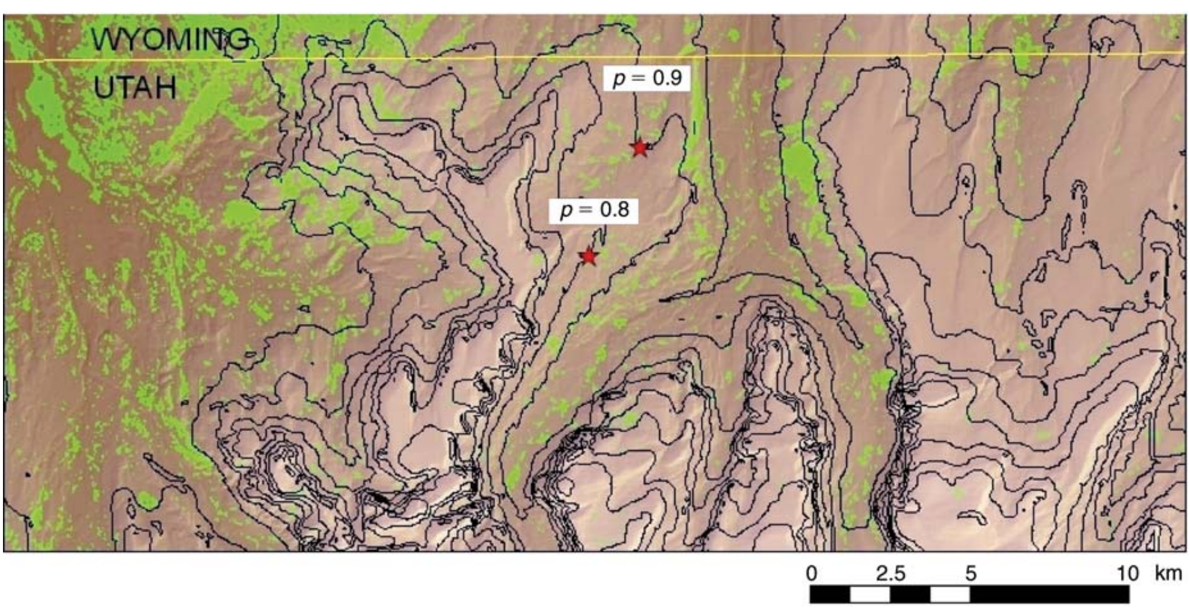

FIG. 8. Gypsy moth hazard in the Lyman Lakes quadrangle, with climate normals projected for the period 2071–2100. Male moth trap recovery locations are indicated by the red stars. Contour lines are indicated in black, with one trap lying on the $p = 0.9$ line and the other on the $p = 0.8$ line, indicating that by 2100 the benign introduction of 2003 would be predicted to be a serious threat. Aspen distribution (Utah GAP data) is indicated by green.

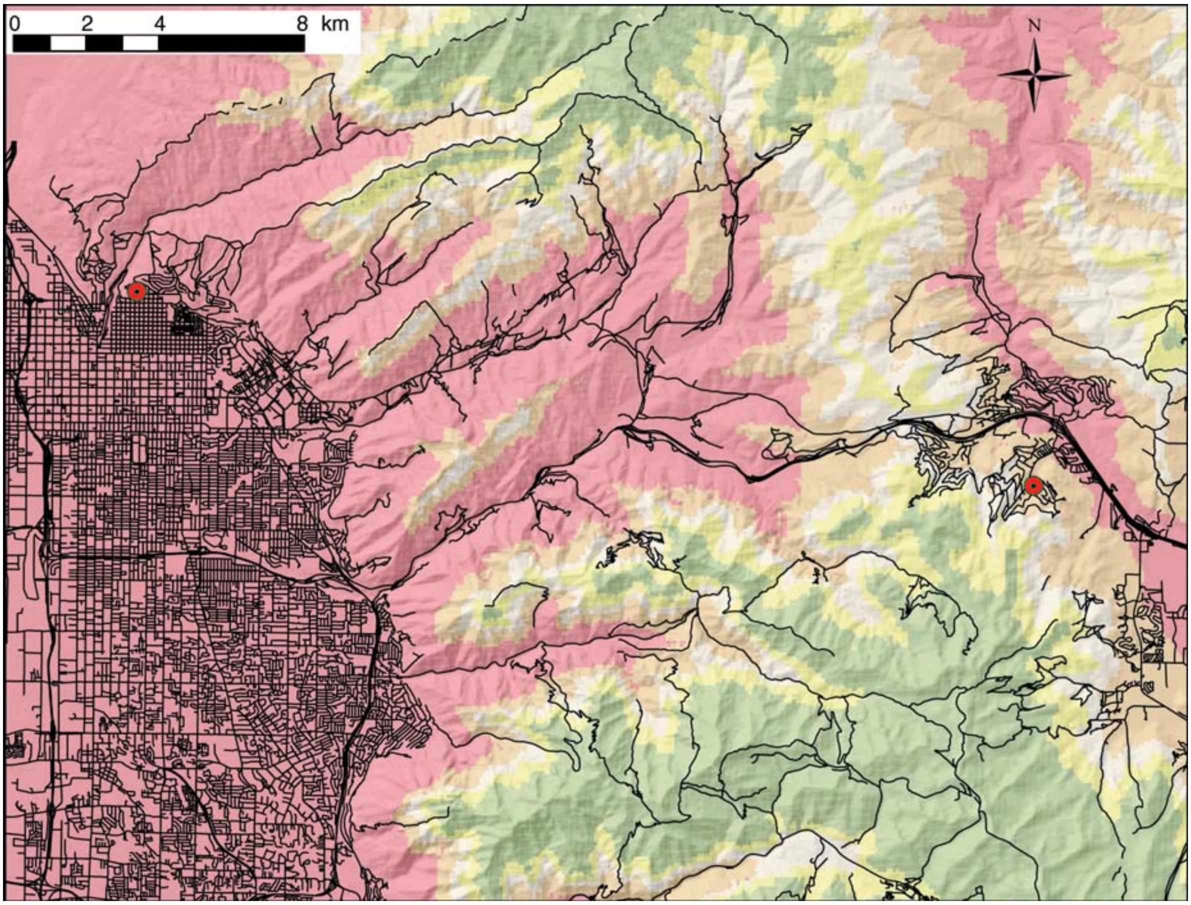

FIG. 9. Gypsy moth hazard map for Salt Lake City, Utah (to the west), and Summit County (to the east). Red indicates the highest hazard zones. Trap sites of 2004 are indicated by the red target circles.

contiguous with the urban sprawl along the Wasatch Front. Of the three primary native gypsy moth hosts in the state, oak is therefore at the highest risk to introduction. The area east of Salt Lake City includes significant native oak. In addition, this oak habitat is contiguous with aspen habitat at higher elevations. Confounding this high-risk geographical configuration is the prediction from both the Canadian and Hadley models for increasing spring precipitation for this region (Mearns 2003*b*, Wagner 2003), and historical trends show a significant increase in spring precipitation as well (Baldwin 2003). Therefore, the native oak habitat may also become increasingly favorable for establishment of introduced gypsy moths. If this scenario plays out, the suitability of future habitat in both oak and aspen will increase, with oak providing an effective conduit from the area of highest probability of introduction around Salt Lake City to aspen at higher elevations. Clearly, additional research is needed that quantifies the stage-specific effects of moisture stress on mortality.

No gypsy moth risk assessment system currently exists for the western United States. Detection trap locations are based on the experience of individuals and on agency protocols. In many western states, traps are placed on a grid system in urban settings and by dispersing a few traps in smaller communities and high-use recreation areas. Grid trapping also occurs near urban areas where forested urban–wildland interfaces exist. Although susceptible vegetation and human population density influence trap placement, many traps are placed in sites where no susceptible host vegetation is present or environmental conditions are not suitable for life stage development.

To minimize detection and delimitation costs, the risk assessment we describe can predict where moderate- to high-risk sites exist, allowing agency officials to select trapping sites based on risk of establishment if the insect is introduced. Likewise, resources can be diverted from low-risk sites to areas where risk of establishment is greatest. In Utah, ~U.S.$150 thousand is spent annually on the detection and delimitation program. Focusing this amount on sites where the risk of establishment is greatest will augment current detection and delimitation efforts. An inadequate monitoring program in Utah resulted in >U.S.$3.6 million of eradication treatments in the late 1980s and early 1990s.

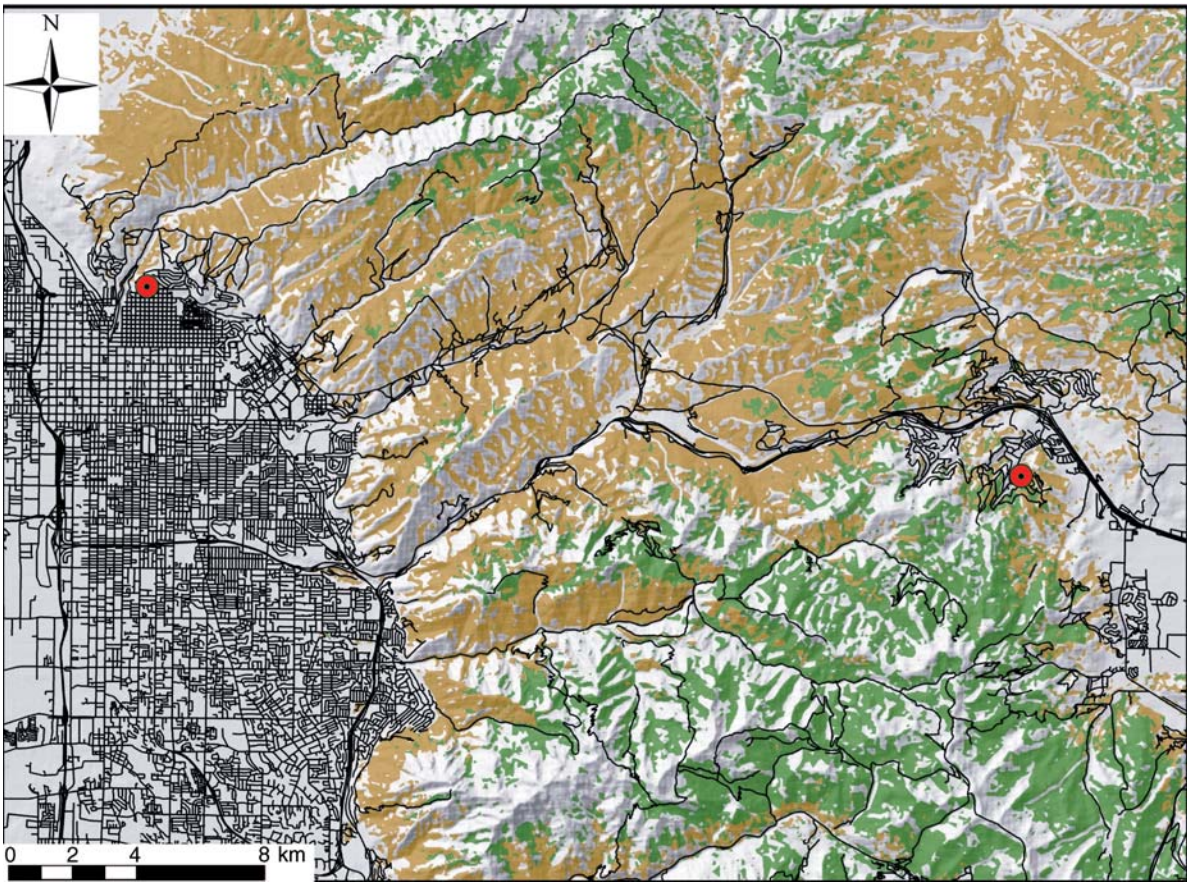

FIG. 10. Salt Lake City and Summit County 2004 trap recoveries (red target symbols) and native host distributions of aspen (green) and oak (orange).

Successfully eradicating an introduced pest requires detecting the introduction early and accurately delimitating the infestation boundaries. Concentrating detection efforts in the areas of greatest risk will allow agency officials to enhance the capabilities of their early detection programs. Likewise, detecting a population shortly after it is introduced will decrease treatment costs associated with an eradication program.

In Utah, agency officials have already spent significant time and resources deploying detection or delimiting traps in sites where the risk of establishment is low. This practice is not unique to Utah, as other western states employ a similar method of deploying detection and delimiting grids in sites that would be rated low risk. Current detection and delimiting protocols are based on the Animal and Plant Heath Inspection Service (APHIS) guidelines for detecting and delimiting gypsy moth populations. The current guidelines do not consider distance to a susceptible host type or temperature/humidity requirements for the insect to successfully complete its life cycle.

Concurrent with global climate change, conditions suitable for gypsy moth establishment will also change. Federal and state regulatory agencies responsible for deploying detection traps do not currently have the tools necessary to predict when or where these changes will occur. The risk assessment system we describe was developed to take these climate-related changes into account for assessing overall risk of gypsy moth establishment. Technology transfer is currently underway to make our modeling approach available to responsible regulatory personnel (the first workshop was held at Utah State University, Logan, Utah, USA, on 24–25 February 2006, sponsored by the Utah Department of Agriculture and Food, USDA Forest Service Forest Health Protection, and Utah State University Forestry Extension).

Although the research we describe here was directed at risk assessment for gypsy moth establishment, the system would provide valuable information for the timing of spray applications in the event an introduction becomes established. Additionally, we described a generalized approach that would be useful for any exotic insect pest. Asian gypsy moth is an obvious case in point. Implications for generalization go even beyond potentially introduced species. Many of the databases and model–GIS interface techniques apply for risk assessment and management of native pest species

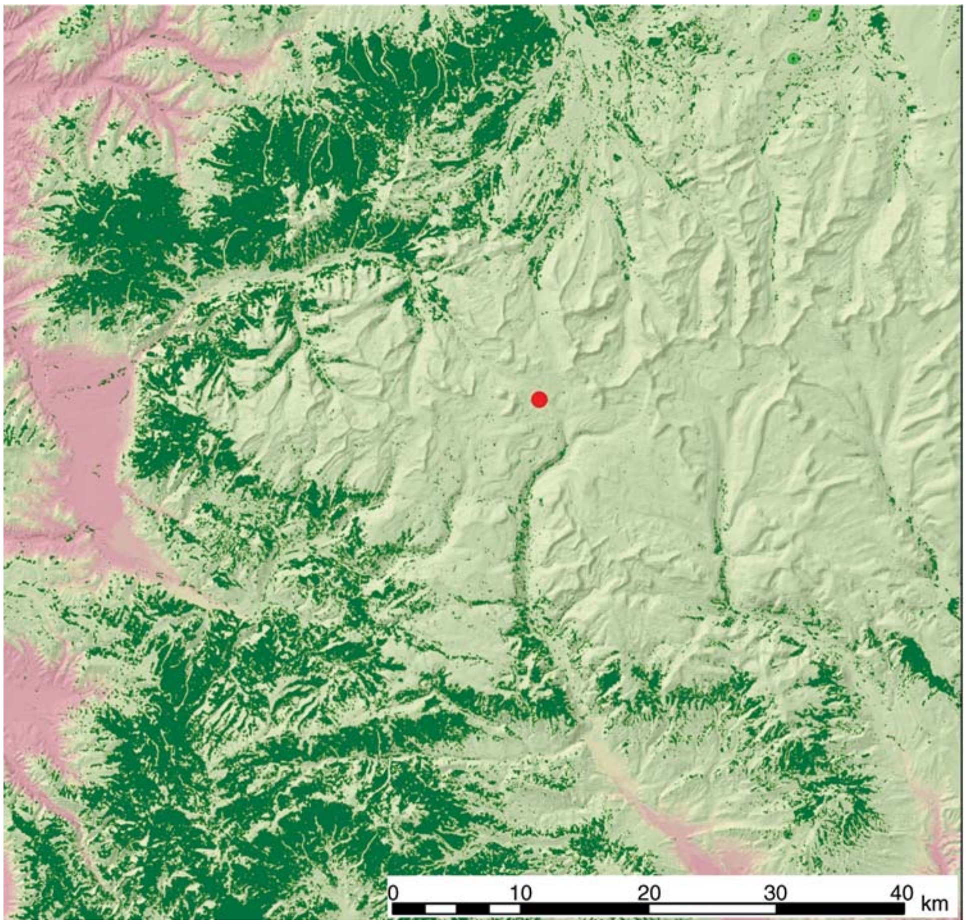

FIG. 11. Mirror Lake 2004 trap recovery site (red circle) in the Uinta Mountains. Aspen distribution (Utah GAP data) is indicated by dark green.

(e.g., shift from semi- to univoltinism in spruce beetle populations [Logan et al. 2003], or range expansion and invasion of new habitats by mountain pine beetle [Logan and Powell 2001]). Research motivated by risk assessment for European gypsy moth introductions is, therefore, readily generalized to other exotic and native species as their ecological associations are modified by, and adapt to, a changing climate.

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