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Quantifying the Capacity for Assisted Migration to Achieve Conservation and Forestry Goals Under Climate Change

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3 Modeling goals of tree assisted migration

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24

25 **Abstract**

26 Aim

27 Many tree species may be threatened with declines in range and biomass, or even extinction, if

28 they cannot disperse or adapt quickly enough to keep pace with climate change. One potential, and

29 potentially risky, strategy to mitigate this threat is assisted migration, the intentional movement of

30 species to facilitate population range shifts to more climatically suitable locations under climate

31 change. The ability for assisted migration to minimize risk and maximize conservation and forestry

32 outcomes depends on a multi-faceted decision process for determining, what, where, and how

33 much to move. We provide an assessment on how the benefits and risks of assisted migration could

34 affect the decision-making process.

35

36 Location

37   Mountainous coastal western United States.

38

39   Taxon

40   Trees

41

42   Methods

43   We used a dynamic vegetation model parameterized with 23 tree species.

44

45   Results

46   We found that most of the modeled species are likely to experience a substantial decline in biomass,

47   with many potentially facing regional extinction by 2100 under the high-emission SSP5-85

48   climate-change scenario. Though simulations show assisted migration had little effect on the

49   forestry goal of total biomass across all species, its effects on the conservation goal of promoting

50   individual species' persistence were far more substantial. Among eight assisted migration

51   strategies (differing in the life cycle stage of movement and target destination selection criteria),

52   the approach that conserved the highest biomass for individual species involved relocating target

53   seedlings to areas that recently experienced fire. Although this strategy significantly reduced

54   extinction risk for six at-risk species compared to no action, it also slightly reduced biomass of

55   four species, due to increasing competition. Species with relatively weak tolerance to drought, fire,

56   or high temperature were the most likely candidate groups for assisted migration.

57

58   Main Conclusions

59   Our simulations indicate that assisted migration (AM) can aid conservation by reducing extinction

60   risks for species vulnerable to climate change, but it has limited impact on forestry-specific goals,

61   affecting overall biomass minimally. This model framework could be applied to other forest

62   ecosystems to evaluate the efficacy of assisted migration globally.

63

64   **Keywords:** Assisted migration, dynamic vegetation model, forestry, climate change, range shift,

65   biomass loss, management

66

67   **Introduction**

68   Climate change poses a significant threat to species unable to adapt, acclimatize, or disperse

69   effectively (Davis Margaret & Shaw Ruth, 2001; Holt, 1990), particularly affecting foundation

70   species like forest trees (Coops & Waring, 2011; Kreyling et al., 2011; Stanke et al., 2021; Tejedor

71   Garavito et al., 2015). This inability can lead to major ecosystem disruptions, as already observed

72   in forests facing severe droughts, altered fire patterns, and increased climate variability (M. I.

73   Williams & Dumroese, 2013). Predictions suggest many tree species' habitats will shift or diminish

74   due to climate change, especially impacting species with poor dispersal abilities, low

75   acclimatization capacity, or limited genetic diversity, potentially leading to range reduction,
76   biomass loss, or extinction (Nathan et al., 2011; M. I. Williams & Dumroese, 2013; Zhu et al.,
77   2012).

78   Assisted migration (AM), or managed relocation, is a proposed strategy to preserve at-risk
79   tree species and ecosystem services by intentionally moving species to more suitable locations
80   (McLachlan et al., 2007; M. I. Williams & Dumroese, 2013). While AM could enhance survival
81   chances of vulnerable species, it is not without risks and has sparked debate over the potential for
82   relocation failures and negative impacts on recipient ecosystems (Champagne et al., 2021; Chen
83   et al., 2021; Hewitt et al., 2011; Kreyling et al., 2011; Minteer & Collins, 2010; Ricciardi &
84   Simberloff, 2009; Richardson et al., 2009; Simler et al., 2019).

85   Assisted migration in forest systems can serve either forestry or conservation goals, or
86   potentially both (Pedlar et al., 2012). Among many other objectives, forestry goals often focus on
87   forest productivity, and conservation goals typically focus on species persistence including targets
88   for range and biomass, with diversity potentially connecting to both goals (M. I. Williams &
89   Dumroese, 2013). Though at some level forestry might prioritize the conservation of particular
90   species and conservation may aim to preserve biomass, in this paper we consider "forestry goals"
91   as synonymous with total biomass conservation and "conservation goals" as synonymous with
92   individual species biomass conservation. AM's effectiveness at species or community levels
93   depends on how relocated populations compete with non-target species and contribute to overall
94   system productivity (M. I. Williams & Dumroese, 2013). Achieving conservation and forestry
95   goals through AM, while reducing associated risks, involves decisions about which species to
96   move, when, where, and how. Suitable candidates for AM include species with poor dispersal
97   ability and low tolerance to heat, drought, or fire, given current and expected climate trends (Clark
98   et al., 2016; M. I. Williams & Dumroese, 2013). Current practices often involve moving seedlings
99   grown in greenhouses or direct seed relocation, which might be more cost-effective in some cases
100   but is also prone to higher early-stage mortality (Castro et al., 2023; Clark et al., 2016; Haase et
101   al., 2019; Mohan et al., 2021; M. I. Williams & Dumroese, 2013).

102   Selecting target (i.e., destination) locations for AM requires considering proximity to
103   historical ranges, canopy cover, recent disturbances like fire, and balancing AM efforts to enhance
104   success while minimizing competition with local species (Pedlar et al., 2012; Welch et al., 2016).
105   Targeting the closest climatically suitable locations (hereafter, the "minimum-distance" strategy)
106   to the introduced species' historical range could reduce the risk of introducing novel competition
107   to species already extant in the recipient community (Pedlar et al., 2012). Another strategy could
108   be to select locations with low canopy coverto reduce light and water competition ("least-
109   competition") and increase establishment success for AM individuals. Considering disturbance,
110   moving target species to sites which recently experienced fire ("post-fire") could take advantage
111   of fire's reduction of canopy and understory cover, as well as the postfire abundance of bare
112   mineral soil (Welch et al., 2016). Finally, moving species to sites with the least expected fire

113 frequency ("least-fire") could reduce the potential for fire disturbance to affect establishment
114 success. A dynamic modeling framework that incorporates dispersal and competition dynamics
115 can quantify these aspects to inform AM implementation (Iverson & McKenzie, 2013).

116   This study used a dynamic vegetation model modified from ForClim v.3.0 to evaluate forestry
117 and conservation outcomes of AM, focusing on decision-making regarding species selection,
118 timing, location, and intensity of relocation. We parameterized the model with 23 major tree
119 species from the western montane regions of the US (Safford et al., 2021), identifying target
120 species for relocation based on projected population declines under future climate change. We
121 chose our focal species because these species represent an array of life history types with enough
122 data to parametrize our model. Note that we make this choice based on current forest composition
123 rather than current conservation status (i.e. we don't only focus on species with low population
124 sizes), for two reasons. First, we wanted to understand the potential effects of AM of at-risk species
125 on the remainder of the community, so we aimed to include a representative community
126 composition of both at-risk and not-at-risk species. Second, theory indicates that life history
127 susceptibility can serve as a better indicator than current abundance for vulnerability to changing
128 future conditions, and data indicate that even abundant foundation species can experience rapid,
129 unexpected declines under extreme climatic events linked to climate change (Hartmann et al., 2022;
130 Hughes et al., 2017; McPherson et al., 2021; Tilman et al., 1994). We considered four types of AM
131 destination site-selection: minimum-distance (MD), least-competition (LC), post-fire (PF), and
132 least-fire (LF) destinations; and two AM types by relocated life stage: seed AM (DA) and seedling
133 AM (GA). We also explored AM intensity regarding frequency, duration, target locations, and
134 individuals moved. Simulating various climate change and AM management strategies, we
135 measured forestry goals in terms of total biomass and conservation goals in terms of individual
136 species biomass, persistence, and both with biomass-weighted gamma diversity. Our core
137 questions are then (1) for each of (a) forestry and (b) conservation goals, and under a range of
138 climate scenarios, how does the effect of engaging in AM, compared to no action, depend on AM
139 strategy for timing and location, (2) for conservation goals, which types of species most benefit
140 from AM, and (3) how does increasing different aspects of AM intensity affect the outcomes for
141 both target and non-target species?

142

143   **Table 1: acronym summary for management strategies.**

Acronym	Full name
AM	**A**ssisted **m**igration
LCDA	**L**east **c**ompetition seed **a**ssisted migration
LCGA	**L**east **c**ompetition seedlin**g** **a**ssisted migration
LFDA	**L**east **f**ire see**d** **a**ssisted migration
LFGA	**L**east **f**ire seedlin**g** **a**ssisted migration
MDDA	**M**inimum **d**istance see**d** **a**ssisted migration

MDGA	**M**inimum **d**istance seedling **a**ssisted migration
PFDA	**P**ost **f**ire see**d** **a**ssisted migration
PFGA	**P**ost **f**ire seedling **a**ssisted migration
CT	**C**on**t**rol group

144
145
146 **Materials and methods**

147 **I. Model overview**

148   Our model simulates forest dynamics of individual trees, climate change, and management
149 actions in R version 3.6.2. The model has four sub-models that change over each one-year time
150 step: (A) the demographic vegetation sub-model in which we simulate plant growth, mortality,
151 dispersal, and recruitment based on the PLANT sub-model from ForClim v.3.0 (Gutierrez et al.,
152 2016), (2) the assisted migration sub-model in which we simulate several approaches to assisted
153 migration, (3) the climate sub-model in which we simulate changing climatic conditions across the
154 spatial and temporal scale of the model based on estimates from the WorldClim dataset (Fick &
155 Hijmans, 2017), and (D) the fire sub-model in which we simulate fire occurrence and fire-induced
156 tree mortality based on the fire sub-model of ForClim (Figure 2). After introducing our study
157 system and spatial structure, the subsequent sections explain these sub-models.

158
159 **II. Study system and spatial structure**

160   We simulated forest dynamics in a large, mostly forested and mountainous region of the
161 Pacific western United States, ranging from Mediterranean scrub to temperate forests. Trees in this
162 region face increasing risks from climate change, including more frequent and intense droughts
163 and wildfires (Mann & Gleick, 2015; Miller et al., 2009), further exacerbated by human activities
164 (Chen et al 2021). The elevational range of this region is 4 - 4421 m, with a mean of 1313 m. This
165 region is home to several tree species vulnerable to range contraction or extinction due to these
166 environmental changes (Loarie et al., 2008; Rogers et al., 2011). Among these AM candidate
167 species are economically important species such as ponderosa pine (*Pinus ponderosa*) and
168 currently rare species like foxtail pine (*Pinus balfouriana*) (Richardson et al., 2009). Because many
169 of these species take decades to reach maturity (Bonner et al., 2008), urgent conservation may be
170 necessary to prevent extinction and loss of ecosystem services (Stephens et al., 2020).

171   We focused on a region made up of two connected line segments (Figure 1, Appendix S1:
172 Figure S1.A), 1 degree longitude in width, following the Sierra Nevada (36°11' N, 119°3' W to
173 41°23' N, 122°47' W) and the Cascade Range (41°23' N, 122°47' W to 48°36' N, 121°39' W). We
174 divided this area into 157320 1-km^2 grid cells (120 wide and 1311 long), each consisting of 200
175 patches (833 m^2 each) in which we simulated forest dynamics representing the mean dynamics of
176 the entire cell (Gutiérrez et al., 2016). While the spatial location of grid cells is explicit, the spatial
177 structure of patches is implicit. In other words, the 200 patches within each grid cell have no precise

178 coordinates, and each of these internal patches share the same climatic conditions based on the
179 coordinates of the grid cell. Though there is no direct interaction between patches, seeds can
180 disperse between grid cells. In the model simulation, we simplified the spatial structure of the study
181 region into a 1311×120 matrix, where the distance between the center of any two neighbor grid
182 cells is 30-arcseconds (i.e., ~1 km).

183 At this 1km resolution scale, we used the LEMMA spatial dataset from the year 2017
184 (generated from FIA dataset and Landsat imagery) for initial species occurrence and basal area
185 estimation (Ohmann & Gregory, 2002), and the WorldClim version-2.1 dataset for elevation data
186 and climate data (Fick & Hijmans, 2017). We modeled 23 typical tree species from the Sierra
187 Nevada and Cascades with accessible physiological parameters (**Table 2**).

188

189

190 [double column] Figure 1: Map of our study region. We focused on a region made up of two connected line
191 segments, 1 degree longitude in width, following the Sierra Nevada (in red color, 36°11' N, 119°3' W to 41°23'
192 N, 122°47' W) and the Cascade Range (in dark green color, 41°23' N, 122°47' W to 48°36' N, 121°39' W).

193

194

195 **Table 2: Species-specific parameter set of 23 tree species used in this study.** Acronyms of columns of traits:
196 minimum growing degree-day requirement ($kDDMin_s$, °C), drought tolerance ($kDrtol_s$), fire tolerance class (kFi_s;
197 as class number increases, fire tolerance decreases), minimum and maximum winter temperature tolerances
198 ($kWiTN_s$ and $kWiTX_s$, °C). See Appendix S1: Section S2 Parameterization for parameter value sources,
199 justification, and calculations.

Scientific name	Common name	Species_id	$kDDMin_s$	$kDrTol_s$	kFi_s	$kWiTN_s$	$kWiTX_s$
Abies amabilis	Pacific silver fir	1	608	0.20	1	-4.8	1.4
Abies grandis	Grand fir	2	595	0.25	2	-5.1	1.4
Abies lasiocarpa	subalpine fir	3	580	0.19	1	-5.1	0.6
Abies procera	Noble fir	4	626	0.21	2	-4.0	1.3
Acer macrophyllum	Big-leaf maple	5	1024	0.47	2	-2.0	5.6
Arbutus menziesii	Madrone	6	1266	0.50	2	0.5	6.2
Chamaecyparis nootkatensis	Alaska cedar	7	577	0.13	1	-5.4	0.9
Picea engelmannii	Engelmann spruce	8	607	0.23	1	-5.0	0.6
Pinus contorta latifolia	Lodgepole pine	9	625	0.33	2	-4.5	1.2
Pinus monticola	Western white pine	10	619	0.32	2	-4.6	1.6
Pinus ponderosa	Ponderosa pine	11	828	0.46	4	-3.4	5.3
Pseudotsuga menziesii menziesii	Pacific coast Douglas-fir	12	727	0.43	3	-3.8	4.4
Quercus garryana	Oregon white oak	13	1241	0.50	4	-1.5	6.0
Tsuga heterophylla	Western hemlock	14	665	0.23	1	-4.6	1.8
Tsuga mertensiana	Mountain hemlock	15	562	0.24	1	-5.1	0.7
Abies concolor	White fir	16	785	0.43	2	-2.9	4.8
Abies magnifica	Red fir	17	687	0.37	3	-3.5	2.0
Calocedrus decurrens	Incense cedar	18	962	0.46	3	-2.2	5.4
Pinus jeffreyi	Jeffrey pine	19	788	0.44	3	-3.0	4.6
Pinus lambertiana	Sugar pine	20	935	0.46	3	-2.6	5.4
Pinus albicaulis	Whitebark pine	21	467	0.23	2	-6.1	-0.2
Quercus kelloggii	California Black oak	22	1204	0.52	3	-1.1	6.4
Pinus balfouriana	Foxtail Pine	23	391	0.32	4	-6.3	-1.4

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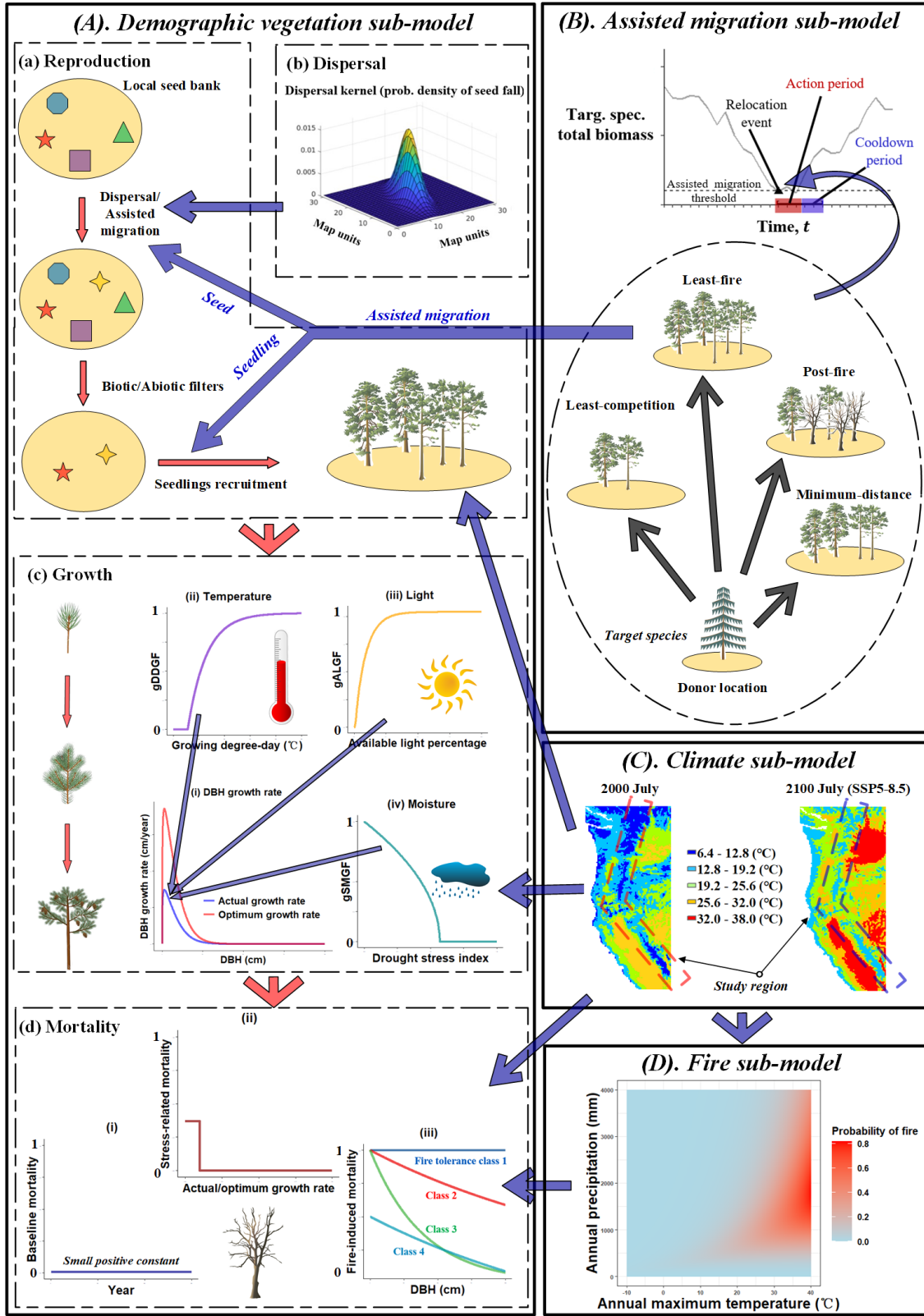
[double column] Figure 2: Model diagram. The model comprises four interconnected components:

202
203

204 demographic vegetation, assisted migration, climate, and fire. The demographic vegetation sub-model (A)

205 includes four processes: (A.a-b) reproduction & dispersal, (A.c) growth, and (A.d) mortality, with each process

206 influenced by local conditions like climate and competition. Reproduction involves a local seed bank and

207 stochastic species addition, while dispersal is wind-driven. Growth depends on limiting factors of temperature

208 (gDDGF), light (gALGF), and soil moisture (gSMGF), affecting tree size. Mortality arises from baseline rates,

209 stress, and fire, with fire tolerance varying by species. Assisted migration (B) is triggered when target species

210 biomass falls below a threshold, considering factors like fire risk and competition for destination selection.

211 This sub-model, along with climate data, affects fire probability and mortality in the fire sub-model (D).

212 Overall, these components are connected by blue arrows, indicating their interdependencies and influence on

213 each other.

214

215

216 **III. Demographic vegetation sub-model**

217   In the demographic sub-model (Figure 2.A), we adapted the PLANT sub-model from ForClim

218 v.3.0 , altering only the recruitment function to include a dynamic seed bank influenced by wind-

219 driven seed dispersal (Gutierrez et al., 2016; Rasche et al., 2012). Therefore, seeds can disperse

220 between different grid cells. Growth and mortality functions remained as in the original ForClim

221 model. We focused on long-distance, wind-driven seed dispersal, excluding animal-based dispersal

222 due to limited data. ForClim's effectiveness in predicting forest species composition and

223 productivity under various climates is well-established, as evidenced in previous studies, including

224 those in the western United States (Harald K. M. Bugmann & Solomon, 2000; Gutiérrez et al.,

225 2016).

226   The ForClim PLANT sub-model simulates forest demographics in independent patches,

227 accounting for tree recruitment, growth, and mortality. Recruitment depends on local and dispersed

228 seeds, with seedling establishment influenced by species-specific environmental responses (see

229 S1.1.1 Tree reproduction). The model simulates diameter at breast height (*DBH*), tree height, and

230 age for each tree. With this information, we can then compute basal area, woody biomass and

231 foliage biomass based on *DBH* and height, using species-specific allometric equations. We

232 assumed species with basal area higher than a threshold T_p in a patch have an effective seed bank

233 in that patch to support their presence, where we use the threshold value that provided the highest

234 accuracy of presence-absence predictions under the ForClim framework (1 m^2/ha; Gutiérrez et al.

235 2016). Here we use basal area as a surrogate for biomass (linear approximation, see Appendix S1:

236 Equation S29 & S30) as well as for tree age to reach reproductive maturity, which is a common

237 forestry practice. In addition, we assume that the seed bank persists for the duration of the

238 simulation, for computational simplicity and in line with existing forest dynamic models (Botkin,

239 Janak, & Wallis, 1972; Harald K. M. Bugmann & Solomon, 2000; Rasche et al., 2012); we test the

240 effect of limited seed bank duration in sample model runs (see Discussion). In the growth function,

241 each individual living tree in the model has a chance to increase in diameter and biomass (see

242   S1.1.2 Tree growth). The optimum tree growth rate mainly depends on net carbon assimilation,
243   following the carbon budget approach by Moore (1989), while light availability across the crown,
244   growing degree-days (GDD) and drought stress limit the realized growth rate. In the mortality
245   function, each individual living tree can experience mortality based on three mechanisms: baseline
246   mortality, stress-induced mortality, and fire-induced mortality (see S1.1.3 Tree mortality).
247   Individuals experience mortality as a binomial draw weighted by the mortality probability.

248

249

250   **IV. Assisted migration sub-model**

251   In the Assisted Migration sub-model of the ForClim framework (Figure 2.B), we focus on the
252   strategic relocation of tree species to new areas in response to declining biomass levels. Following
253   the model developed by (Backus & Baskett, 2021), AM interventions occur when a species'
254   biomass falls below a predefined threshold (see Table 3). The model operates on a cycle of action
255   and rest: relocation actions are taken for a specified number of years (I_a), followed by a cooldown
256   period (I_c) of no relocations. This allows the relocated species time to establish in the new
257   environment. The lengths of the action and cooldown periods are consistent across species and are
258   detailed in Table 3. While the thresholds for implementing assisted migration are deterministic,
259   when AM then occurs then inevitably varies with the variability inherent to the ecosystem (e.g,
260   with fire occurrences and changes in temperature). This approach is analogous to other threshold-
261   based (i.e., based on "trigger reference points" or "decision triggers") approaches to conservation
262   and natural resource management (e.g., harvest control rules dependent on overfishing limits in
263   fisheries, endangered species delisting criteria in recovery plans, or forestry replanting guidelines
264   associated with minimum acceptable stocking rates [live trees per acre] (Cook et al., 2016; Irwin
265   & Conroy, 2013; Stoel, 1978)).

266

267   **Table 3: non-species-specific parameters used in the model, symbols used to represent them, values used,**
268   **and units of these parameters.** See Appendix S1: Section S1.1 Demographic vegetation sub-model for more
269   detailed description and sources of these parameters.

Parameter	Symbol	Values	Units
Maximum number of newly established seedlings of one species in one patch	N_{max}	5	individuals
Minimum basal area threshold for tree species presence	T_p	1	m²/ha
Mean wind speed across our study region	u	5.689	m/s
Standard deviation of the vertical velocity of the air	σ	0.25	(m/s)²
Turbulence coefficient used to calculate dispersal kernel	κ	0.4	-
AM threshold (percentage of initial species-specific biomass)	T_{AM}	30	%
Number of simulated patches used to represent one grid cell	N_{pa}	200	-
Area of each patch	A_{pa}	833	m²
Years per relocation	I_a	2, 4, …, 10	years
Minimum years between relocation	I_c	4, 8, …, 20	years

Number of target grid cells for AM	N_{gc}	3, 6, …, 15	grid cells
Number of seedlings of the target species moved to one patch during seedling AM	N_{sd}	80, 160, …, 400	individual

270

271   To estimate suitable target sites for the target species under future climate conditions, we

272 selected grid cells in which the projected bioclimatic conditions in 2100 were within the species'

273 climatic tolerance range. During each year within the relocation period, we set the number of target

274 grid cells for AM as N_{gc}. We simulated AM of two life stages in this sub-model, namely, seed and

275 seedling. We simulated seed assisted migration (DA) by modifying the seed bank (relative

276 recruitment) of the AM target species in the target grid cell, which gives the target species a relative

277 recruitment advantage, namely a 30 times higher recruitment rate than other present species (even

278 if the target species was not already present in the seed bank). For seedling assisted migration (GA),

279 we based our simulation on the common practice in forestry of cultivating seedlings in a

280 greenhouse for several years (Haase et al., 2019) before moving them to a target location. In our

281 model, we simulated this by directly moving a certain number (N_{sd} x 200) of seedlings of the target

282 species with *DBH* = 1.27 *cm* (average size of cultivated seedlings among different tree species

283 (Sáenz-Romero et al., 2021)) into a target grid cell, omitting the greenhouse cultivation processes.

284 The number of seedlings moved to one patch was N_{sd}, while 200 is the number of patches within

285 one grid cell. During an AM period, this sub-model simulates seed or seedling AM on all N_{gc} target

286 grid cells.

287   We model four strategies for choosing relocation destinations. Minimum-distance

288 destinations (MD) focus on proximity, selecting grid cells closest to the species' current range.

289 Least-competition destinations (LC) prioritize areas with the lowest existing tree biomass,

290 reducing competition for resources. Post-fire destinations (PF) are areas recently affected by fire

291 within the species' potential range. Least-fire destinations (LF) are the opposite, selecting grid cells

292 with the least recent fire activity, which also generally had the lowest fire probability among the

293 four destination types (Appendix S1: Figure S7). We evaluate each strategy in combination with

294 the two life stages (DA for seeds, GA for seedlings), resulting in eight distinct AM strategies.

295 Additionally, a ninth control strategy (CT) represents a scenario of no action. Our goal is to

296 determine the most effective AM strategy under varying environmental conditions and species-

297 specific factors. The full methodology and detailed analysis of the results are in Appendix S1:

298 Section S1.2.

299

300 **V. Climate sub-model**

301   We used the Environment sub-model of ForClim V3.0 for our Climate sub-model (Rasche et

302 al., 2012). This sub-model calculates basic bioclimatic data needed by the Demographic Vegetation

303 sub-model, namely minimum winter temperature, growing degree days, and drought index, which

304 affect species recruitment, growth, and mortality, as well as fire probability. We calculated the local

305 climate conditions in each cell using raw bioclimatic data from WorldClim. For each cell in our

306   model, we calculated the long-term minimum winter temperature as the minimum among the mean
307   monthly temperatures of December, January and February over the years 1970-2000. We used the
308   mean monthly temperature to calculate the growing degree days, and we used the mean monthly
309   temperature and precipitation to calculate the drought index following the methods of Bugmann
310   and Cramer (1998) (H. Bugmann & Cramer, 1998). For detailed description of this sub-model, see
311   previous research using ForClim (H. K. M. Bugmann, 1996; Harald K. M. Bugmann & Solomon,
312   2000) and Appendix S1: Section S1.3 Climate sub-model.
313
314   **VI. Fire sub-model**
315   In the fire sub-model (Figure 2.D), we simulate tree mortality due to fires in each time step,
316   influenced by the Climate sub-model's environmental inputs. This sub-model consists of two parts:
317   fire regime dynamics and fire-induced mortality. We base fire regime dynamics on the PC2FM
318   model, which calculates annual fire probability within each grid cell using temperature,
319   precipitation, and elevation data (Guyette et al., 2017). When a fire occurs, tree mortality
320   probability depends on the species' fire tolerance class, fire severity, and tree diameter at breast
321   height (*DBH*). There are two types of fire severities: light (ground fires) and severe (stand-
322   replacing crown fires), with an assumed occurrence ratio of 2:1, based on regional empirical data
323   (Safford et al., 2021). Fires affect every tree in a grid cell. We validated the fire sub-model by
324   comparing modelled fire area with the actual fire area from 2001 to 2020 (Appendix S1: Figure
325   S8). Individual trees living in each grid cell then had an additional probability of mortality within
326   the mortality function of the Demographic sub-model (Busing & Solomon, 2006). To determine
327   each tree's chance of mortality, we divided 23 tree species into four fire tolerance classes, based
328   on the categories given by Busing & Solomon (2006) and fire tolerance data from both Busing &
329   Solomon (2006) and the USDA Fire Effects Information System (Cooke et al., 2015). kFi_s is the
330   fire tolerance class of species s, with class 1 being the least tolerant and most likely to be killed by
331   fire. All fire tolerance classes except class 1 exhibit a decrease in mortality probability with
332   increasing tree size (i.e. *DBH*). For details see Busing & Solomon (2006) and Appendix S1:
333   Section S1.4.
334
335   **VII. Model analysis**
336   For our model validation, we simulated forest dynamics over a century under the current
337   climate (1970-2000 average) as detailed in Appendix S1: Section S3. In short, we validated the
338   model by testing its performance on reproducing current species distribution ranges and basal area
339   distributions. The model provided relatively accurate predictions on both metrics: the Cohen's
340   kappa values (used to measure the agreement between observed and modelled species occurrence,
341   with values > 0.4 indicating a fair degree of agreement; values < 0.2 indicate performance no better
342   than random) for species-range analysis were greater than 0.2 for 17 out of 23 species, which
343   significantly outperform a locally parameterized dynamic vegetation model (kappa > 0.2 for 9 out

344 of 18 species), and are fairly comparable with a regionally parameterized dynamic vegetation
345 model (kappa > 0.2 for 15 out of 18 species) (Cohen, 1960; Gutiérrez et al., 2016). In addition, R^2
346 for comparison between , predicted basal area vs. observation were higher than 0.3 for 20 out of
347 23 species and higher than 0.5 for 15 species.

348   We then initialized future projections incorporating initial seed banks and fire dynamics, and
349 ran simulations under the eight Assisted Migration strategies plus the no-action control scenario,
350 beginning from the year 2000 across 100 years of climate change. We used 1km resolution climate
351 data from WorldClim data (Fick & Hijmans, 2017) of CanESM5-SSP245 (optimistic, with
352 moderate greenhouse gas mitigation) and CanESM5-SSP585 (business-as-usual emissions)
353 scenarios. We chose CanESM because it provides the projection closest to the average outcomes
354 among ten different climate projection models selected for their historical performance in the
355 region (Pierce et al., 2018; Swart et al., 2019), as we sought to use a more typical than extreme
356 expectation for future climate outcomes. To create an annual time series of climate data across 100
357 years, we performed a linear interpolation based on climate data of five key years (2000, 2040,
358 2060, 2080, 2100) for each emissions scenario.

359   In our simulation, we begin by establishing an initial seed bank and seeds, utilizing
360 distributions from the LEMMA database. Each simulation time step involves the growth and
361 mortality of stems, as dictated by the demographic vegetation model. Concurrently, we simulate
362 fire events to account for additional mortality due to fire. Following this, new seeds disperse, which
363 leads to updates in the seed bank compositions. If any species' biomass falls below a critical
364 threshold, we relocate it according to the assisted migration strategy being modeled. Finally, the
365 climate changes according to linear interpolations of WorldClim data, and we start the next time
366 step.

367   To answer our first question regarding the effect of AM on each of forestry and conservation
368 goals for different AM strategies for location and timing, we conducted 100 replicates for each of
369 the nine management scenarios under each emissions scenario. Outputs measured included total
370 biomass (forestry-focused), species-specific biomass (conservation-focused), and gamma
371 diversity weighted by biomass (relevant to both forestry and conservation). AM's effects on total
372 biomass and gamma diversity were similar, differing from its impact on species-specific biomass.
373 Therefore, we used total biomass and gamma diversity for forestry outcomes and focused on
374 species-specific biomass for conservation outcomes.

375   We then analyzed the best-performing strategy, PFGA, under the CanESM5-SSP585 scenario,
376 to explore the traits that influenced which species most benefited from AM and the effect of AM
377 intensity. We chose this scenario for its sufficient climate change impacts on species-level biomass,
378 allowing for a meaningful analysis of AM strategies. To answer our second question regarding
379 which types of species most benefit from AM, we performed a principle components analysis of
380 the average number of relocations per species as it depended on climatic-tolerance parameters
381 (minimum growing degree-day requirement, drought tolerance, fire tolerance, and

382 minimum/maximum winter temperature tolerances). To answer our third question regarding the
383 effects of different aspects of AM intensity, we varied AM intensity in terms of the frequency and
384 duration of AM actions (values of I_c and I_a) and the number of seedlings (N_{sd}) and target sites (N_{gd})
385 implemented.
386
387 **Results**
388 **Forestry-oriented outcomes**
389   On average, the total biomass decreased by ~70% over the 100 years of simulated climate
390 change in the higher emission SSP585 scenario, regardless of management approach (Figure 3).
391 By contrast, gamma diversity remained almost the same as the initial state in the SSP585 scenario.
392 Under the SSP245 scenario, both total biomass and gamma diversity in 2100 remained almost the
393 same as the conditions in 2000. Different AM strategies had a negligible effect on total biomass
394 and gamma diversity. This lack of difference occurs because, while AM can affect individual
395 species' outcomes for a few particularly vulnerable species as detailed below, without AM
396 affecting those species, growth in other species with less vulnerability to climate change
397 counterbalances the loss of vulnerable species to lead to little change in community-level biomass-
398 based metrics. Therefore, for our forestry-oriented metrics (question 1(a)), AM had little effect on
399 the outcome compared to no action, regardless of AM strategy (Figure 3).
400
401
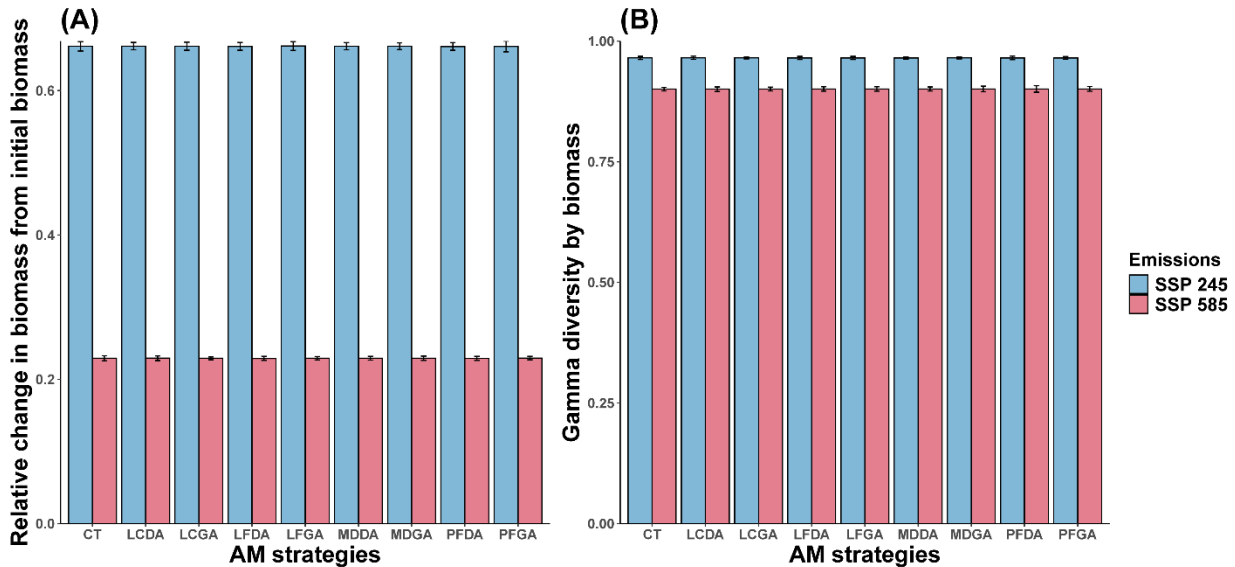
402
403 **[double column] Figure 3: Forestry-oriented outcomes using different AM strategies under two climate**
404 **change scenarios**: **SSP245 (moderate climate change; circles) and SSP585 (business-as-usual climate**
405 **change; triangles)**. (A) Relative change in biomass from initial biomass (the biomass of all trees after 100 years
406 relative to the initial biomass), and (B) gamma diversity by biomass ratio over the same period. Results show

407 average values with standard deviation. AM strategies are grouped by destination criteria (LC: least-competition;
408 LF: least-fire; MD: minimum-distance; PF: post-fire) and method (seeds: DA, seedlings: GA), including a
409 control group (no intervention: CT)..
410
411

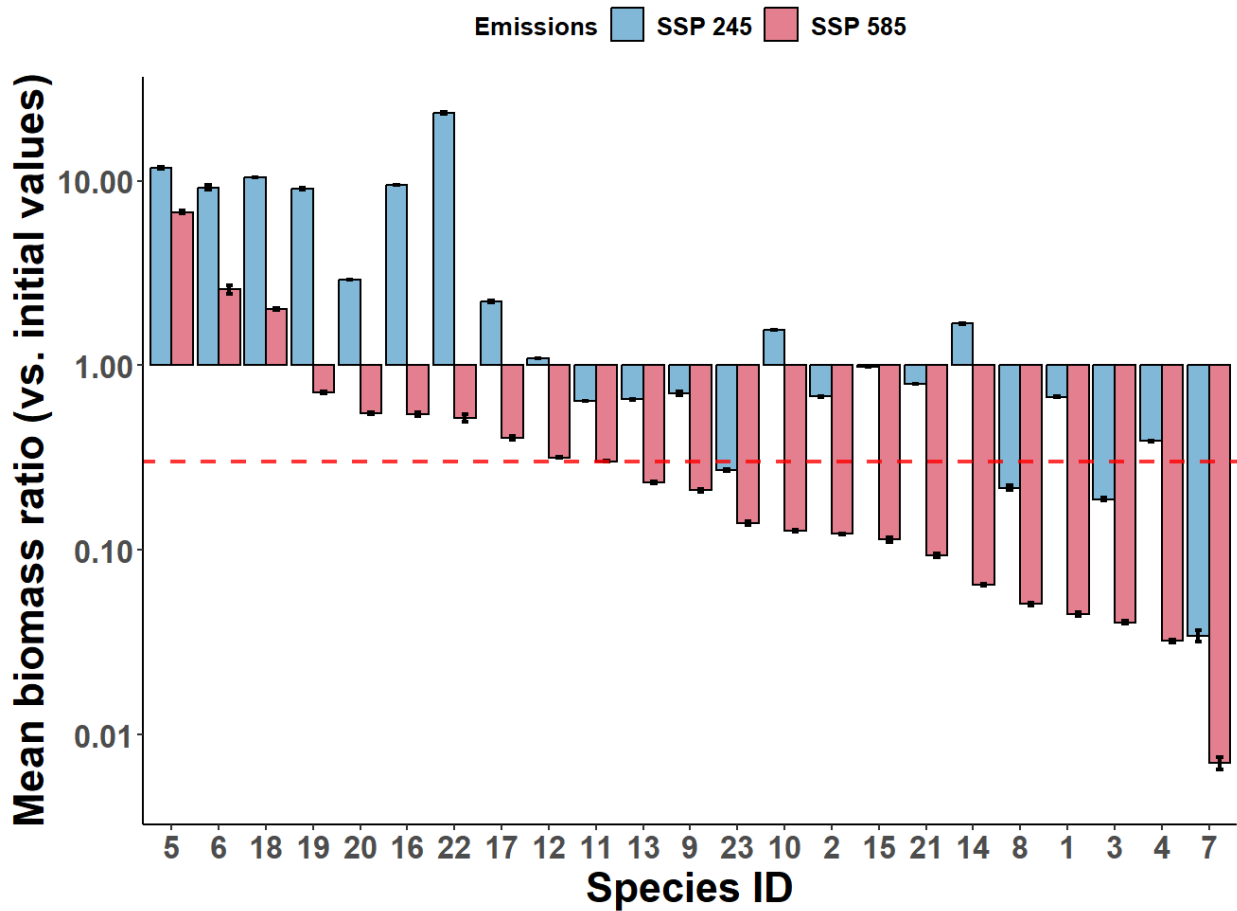412 **Conservation-oriented outcomes**
413   Under the SSP245 climate scenario, about half of the simulated species decreased in biomass,
414 while the other half increased (Figure 4). Species like *Quercus kelloggii* (species 22), *Acer*
415 *macrophyllum* (5), *Arbutus menziesii* (6), and *Calocedrus decurrens* (18), with their relatively high
416 tolerance to drought, heat, and fire (Figure 4), showed biomass gains. A few species, such as
417 *Chamaecyparis nootkatensis* (7), experienced declines below the level that triggered AM actions
418 (Figure 4). In contrast, in the SSP585 scenario, 14 species experienced significant (>70%) biomass
419 reductions (Figure 4). Seven of these, including various *Abies* and *Picea* species, faced a high risk
420 of local extinction, with over 90% biomass decrease. They frequently fell below the AM action
421 threshold.
422
423

424

[double column] Figure 4: Conservation-oriented outcomes of biomass for the control group (no AM) in simulations under SSP245 and SSP585 climate change scenarios. The y-axis indicates relative change in species-specific biomass from initial biomass (the biomass of all trees after 100 years relative to the initial biomass). Blue bars indicate simulations with dispersal (mean ± sd), red bars without. Red dashed lines mark the AM threshold. Species IDs on the x-axis are ordered by mean biomass ratio under SSP585 emission scenario.

434
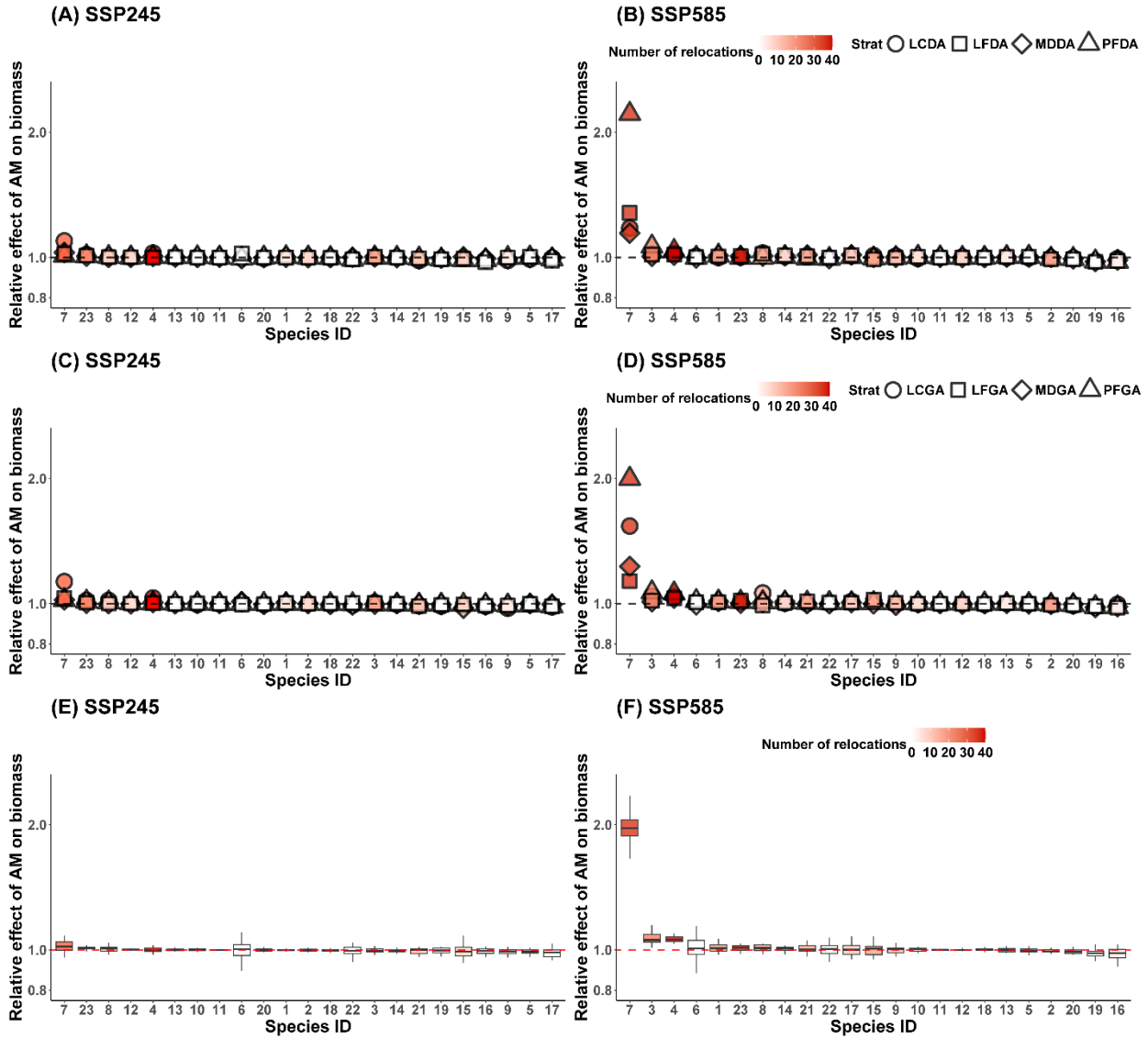
[double column] Figure 5: Conservation-oriented outcomes using different AM strategies under two climate change scenarios: SSP245 (left column) and SSP585 (right column). Relative effect of AM on biomass (species-specific biomass in 2100 under each AM strategy divided by species-specific biomass without AM) are shown on a log10 scale; horizontal dashed lines indicate equal biomass with and without AM. If the biomass ratio > 1 for an AM strategy, it means it performs better than no AM actions. Dot/bar colors represent the frequency of AM for each species, and shapes in panels A-D indicate AM strategies. Panels A-B and C-D display relative effects for AM at seed and seedling stages, respectively, averaged over 100 repetitions. Panels E-F feature boxplots of relative effects under the optimal post-fire seedling AM strategy (PFGA). Species identities for x-axis numbers are in Table 2.   Effects of AM are small except for species 7, 3 and 4 under SSP585 scenario.

445

446

447   Throughout the simulations, 15 out of 23 species underwent relocation at least once (Figure

448   5). However, only a few, such as *C. nootkatensis* (7), *Abies lasiocarpa* (3), and *A. procera* (4),

449   consistently benefited from AM, with *C. nootkatensis* (7) showing the most significant

450   improvement, especially for SSP585 (Figure 5.B,D,F). On the other hand, *Abies concolor* (16)

451   displayed lower biomass under some AM strategies compared to no action.

452   For SSP585, post-fire seedling AM and post-fire seed AM were generally the most effective

453   strategies in increasing species-specific biomass (Figure 5.B&D).. For SSP245, the least-

454   competition seed or seedling strategies were the most effective strategies (Figure 5A&C), but their

455   effect on target species' biomass was much smaller than the effect of AM on biomass for SSP585.

456   Overall, for our conservation-oriented metrics (Question 1(b)), the effectiveness of AM varied by

457   climate scenario, AM strategy, and species, with only a subset of species showing substantial

458   benefits under more extreme climate change (Figure 5), highlighting the role of targeted and

459   species-specific AM strategies under different climate change scenarios.

460

461   **Types of species that benefit from AM**

462   For the most effective AM strategy (post-fire seedling AM), our principal component analysis

463   showed that species that were often relocated in our model had similarly low values on dimension

464   1, which accounted for 79.7% of variance (Figure 5). Low values in dimension 1 implied species

465   were drought-intolerant, fire-intolerant, and cold-adapted. Accordingly, *C. nootkatensis* (7), one of

466   the least drought/fire-tolerant species, benefited the most from AM as noted above (Figure 5).

467   Conversely, species like *A. macrophyllum* (5), with high drought and heat tolerance, thrived under

468   future climate conditions (Figure 4). In sum, our analysis found that species which are poorly

469   adapted to drought, fire, and warmer conditions were more likely to face local extinction without

470   AM intervention and to benefit from AM intervention compared to other species we modeled
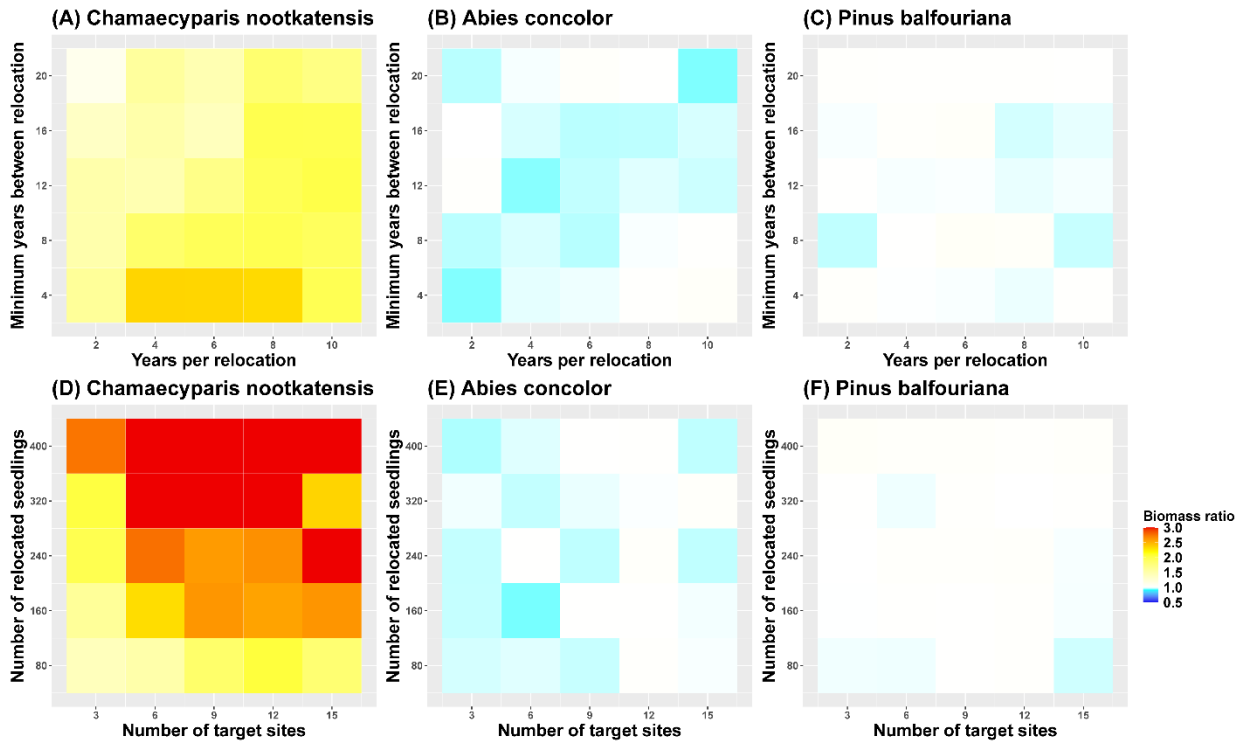
471   (Question 2; Figure 6).

472
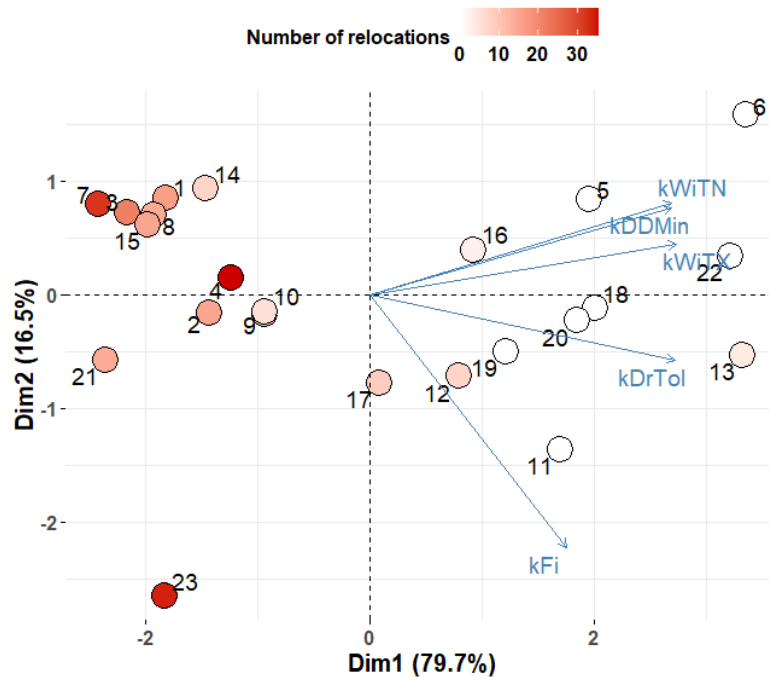
[single column] Figure 6: Principal component analysis of species-specific climatic-tolerance parameters. Dot colors represent the average number of relocations per species under the post-fire seedling AM strategy (PFGA) over 100 repetitions, with numbers indicating tree species. More relocations suggest higher local extinction risk. Parameters include minimum growing degree-day requirement (kDDMin), drought tolerance (kDrTol), fire tolerance (kFi), and minimum/maximum winter temperature tolerances (kWiTN, kWiTX). Tree species identities for each number are detailed in Table 2.

AM intensity

In the analysis of different AM durations, neither years per relocation nor minimum years between relocation had a prominent effect on the total biomass ratio and gamma diversity by biomass (see Appendix S1: Figure S8). More consecutive years per relocation and fewer years between relocations increased the biomass ratio of *C. nootkatensis* (7, Figure 7.A), and *A. procera* (4, Appendix S1: Figure S5). AM strategies with more seedlings and more destinations increased the biomass ratio of *C. nootkatensis* (7, Figure 7.D), *A. amabilis* (1), *A. lasiocarpa* (3) *and A. procera* (4) (Appendix S1: Figure S6). These species are all AM target species with weak heat, fire, and/or drought tolerance. In comparison, species with more moderate-to-high tolerances (e.g., *A. concolor,* Figure 7.B&E and *P. balfouriana*, Figure 7.C&F) displayed no consistent trends in response to increased AM intensity, neither benefitting significantly nor experiencing adverse effects. Therefore, multiple approaches to increasing AM intensity benefited at-risk species, with minimal effects on non-target species (Question 3; Figure 7).

[double column] Figure 7: The effect of AM intensity on conservation-oriented outcomes of PFGA under the CanESM5-SSP585 scenario. Panels A-C depict color maps illustrating species-specific biomass ratios (biomass in 2100 using post-fire seeding (PFGA) divided by biomass with no AM). These maps focus on the effects of years per relocation and minimum years between relocations on three species with varying tolerances: *Chamaecyparis nootkatensis* (low tolerance to heat, fire, drought), *Abies concolor* (moderate tolerance), and *Pinus balfouriana* (moderate drought, high fire tolerance). Panels D-F assess how the number of relocated seedlings and target sites influence species-specific biomass ratios for these species..

Discussion

Our simulations indicate that assisted migration can aid conservation by reducing extinction risks for species vulnerable to climate change, but it has limited impact on forestry-specific goals, affecting overall biomass minimally. The effect of AM arises from the significant impacts of climate change on montane forests in the western United States predicted by our simulations. Under the SSP585 scenario, we observed a dramatic ~70% decline in total tree biomass. Conversely, under the SSP245 scenario, biomass and gamma diversity showed little change. Previous studies support these findings. Loarie et al. (2008) predicted major range reductions for numerous endemic plant species in California and southern Oregon due to climate change. Lenihan et al. (2008) and Rogers et al. (2011) forecasted potential net carbon losses in California forests by 2100, depending on the climate scenario. In contrast, Zhu et al. (2018) suggested a possible ~40%

517   increase in forest biomass in Sierra Nevada and Cascades by 2080 under the RCP8.5 scenario, due
518   to warming and forest recovery from agricultural land. However, this study did not account for
519   disturbances like fires, insect outbreaks, and drought. Recent data shows a 6.7% loss in California
520   forest cover from 1985 to 2021, mainly due to wildfires (Wang et al., 2022). Additionally, Steel et
521   al. (2022) reported that 30% of conifer forests in the southern Sierra Nevada transitioned to non-
522   forest vegetation between 2011-2020, primarily due to drought-related tree mortality and wildfires.
523   While future forest biomass trends carry some uncertainty (Lenihan et al., 2008; Zhu et al., 2018),
524   the majority of projections and trend analyses suggest a significant decline in biomass (Rogers et
525   al., 2011; Wang et al., 2022; J. N. Williams et al., 2023), underscoring the potential value of
526   management strategies like assisted migration.

527   Our simulations showed that under a business-as-usual climate scenario, 15 out of 23 species
528   would face significant biomass reduction. This aligns with previous studies that have documented
529   population declines in similar species due to climate-induced disturbances (Coops & Waring, 2011;
530   Loarie et al., 2008; Stanke et al., 2021). For instance, Stanke et al. (2021) noted declines in *A.
531   lasiocarpa*, *P. engelmannii*, and *P. contorta latifolia*, while Coops & Waring (2011) predicted a
532   40%-50% range reduction for *P. contorta latifolia* and *P. ponderosa* by 2080 in the Northwestern
533   US under similar climate scenarios, assuming no dispersal.

534   AM in our simulations effectively reduced extinction risks for certain species by enhancing
535   their biomass. *C. nootkatensis* (7), for example, showed significant biomass increases (60% and
536   120% higher than no action scenarios under optimistic and business-as-usual climates,
537   respectively). AM also supported biomass retention in *A. lasiocarpa* (3) and *A. procera* (4) under
538   the business-as-usual scenario. However, the overall ecosystem impact of AM was limited,
539   resulting in only slight increases in total biomass and gamma diversity.

540   Interestingly, AM led to biomass declines in four species, possibly due to increased
541   competition from other relocated species. The most significant conservation benefits of AM were
542   observed for species intolerant to fire, drought, and heat, particularly when targeting post-fire
543   locations and implementing AM with greater frequency, number of relocated individuals, and
544   number of target locations.

545

546   *Candidate species for AM*

547   Our model identified species with low tolerance to drought, fire, and high temperature as the
548   most vulnerable species to climate change, making them prime candidates for AM to be relocated
549   to more climatically suitable habitat. This aligns with predictions from previous Species
550   Distribution Models (SDMs) that these species may face severe declines in biomass and range
551   under a business-as-usual climate scenario (Coops & Waring, 2011; Stanke et al., 2021). Our
552   dynamic model, accounting for competition and dispersal, suggests that natural dispersal is too
553   slow to keep pace with rapid climate change for these at-risk species (Figure S10), reinforcing
554   findings from earlier studies.

555   In our model, these at-risk species with low tolerance to fire, drought, and/or heat then
556   benefited most from AM. To identify potential AM candidates in other ecosystems, one could
557   employ a phylogenetic approach to pinpoint clades sensitive to these stresses (Niinemets &
558   Valladares, 2006). Alternatively, a trait-based analysis could estimate climatic tolerance for each
559   tree species. For instance, thin bark is often a marker of low fire resistance (Kidd & Varner, 2019;
560   Stevens et al., 2020), so species with such traits could be considered for AM in systems with fewer
561   available data. Note that these suggestions are speculative and require further research to validate
562   their effectiveness before implementation in forest management practices.

563

564   *Optimal approaches for AM*
565   In our model, the most effective AM strategies were post-fire seedling AM and post-fire seed
566   AM (Figure 5). These methods likely do well due to reduced establishment failure and reduced
567   competition for transplanted trees. In our model, the effectiveness of seed dispersal (e.g., via
568   drones) post-fire was comparable to moving greenhouse-cultivated seedlings, suggesting an
569   alternative to the conventional approach. However, current seed-based propagation has seen
570   limited success in forestry, and drone-based seeding lacks definitive field-based analysis of success
571   (Castro et al., 2023).
572   Seedling survival and growth are typically hindered by surrounding vegetation (due to light
573   competition) and are enhanced by canopy openness (Berkowitz et al., 1995; Duclos et al., 2013;
574   Gerhardt, 1996). Our post-fire AM strategies target recently burned areas with lower biomass and
575   higher canopy openness (Figure S7), providing relocated seeds or seedlings with more light and
576   other resources. Although our model does not account for water competition, soil water availability
577   is also often higher in recently burned forests, where water withdrawals by living vegetation have
578   been reduced (e.g., (Cardenas & Kanarek, 2014)). At the same time, water stress in exposed, highly
579   insolated burned sites can be very high in the dry season, negatively impacting seedling survival
580   (Shive et al., 2018); our model does not account for topographically driven soil water availability.
581   Least-competition AM strategies also performed well, targeting areas with minimal biomass
582   and hence reduced competition. However, these strategies often relocate species to higher
583   elevations with less suitable temperatures (Figure S7), slightly diminishing their effectiveness
584   compared to post-fire AM.

585

586   *Accounting for the risks of AM*
587   Our model highlights two risks of assisted migration: establishment failure for target species
588   and increased competition with non-target species. For instance, *A. grandis* (2) showed no biomass
589   change during simulations, suggesting establishment failure. This is likely due to harsh 2100
590   climates under the SSP585 scenario, with suitable habitats shifting outside our study region, as
591   also projected in other studies (Coops & Waring, 2011). Such conditions may permit survival but
592   hinder seedling establishment. Identifying species unlikely to benefit from AM is as crucial as

593 finding suitable targets, considering AM's costs.

594   Additionally, our model indicates increased competition risks to non-target or target species.
595 For example, under all eight AM strategies in the SSP585 scenario, *A. concolor* (16) and *P. jeffreyi*
596 (19), predominantly located in southern California and the Sierra Nevada, showed reduced
597 biomass compared to no action. This decrease might result from establishment failures at AM
598 destinations and increased competition from other AM-targeted species within their current range.

599
600
601

602 *Potential effects of model assumptions*

603   Our model, while comprehensive, is based on several simplifying assumptions, which can
604 inevitably affect our conclusions. First, our climatic data resolution is 1km, which averages over
605 microclimatic variations (i.e., due to elevational or topographic changes) that affect tree
606 demography (De Frenne et al., 2019; Fick & Hijmans, 2017). Cooler, wetter microclimates can
607 buffer macroclimate effects, potentially leading our model to overestimate negative climate change
608 impacts on seedling/sapling survival and, consequently, forest biomass and range loss. On the other
609 hand, assisted migration strategies that are focused on relocation to open-canopy areas, such as the
610 least-competition and post-fire strategies, will likely be riskier in warmer, drier microclimates. Our
611 model ignores microclimatic variation on the landscape, and assumes that dry and moist
612 microclimates balance each other out at the landscape scale.

613   Second, due to the lack of data, our model does not include the effects of non-fire disturbances,
614 such as those arising from pests, pathogens, or seed predators, despite their significant role in forest
615 dynamics (Bentz et al., 2010). In particular, we did not model bark beetles and diseases like white
616 pine blister rust and Sudden Oak Death, which are prevalent in the North American Mediterranean
617 Climate Zone (NAMCZ) (Berner et al., 2017; Negrón et al., 2009). This exclusion likely leads to
618 an underestimation of tree mortality and extinction risks, and therefore a potential underestimation
619 in AM frequency. Bark beetle and disease susceptibility could also be considered in choosing AM
620 target locations to minimize infection risks, but this raises the issue of potentially spreading
621 diseases through translocated seedlings. Furthermore, our model's coarse scale does not account
622 for the critical role of soil microsites in seed germination and survival (Castro et al. 2023).
623 Incorporation of these additional drivers of forest dynamics and their connections to climate
624 change could expand the primary factors that influence vulnerability to climate change beyond the
625 three modeled here (drought, fire, and temperature tolerance).

626   Third, our study's spatial limits are defined by geographic and political boundaries, not
627 ecological properties. This limitation is especially relevant for species like *A. lasiocarpa* in the
628 western United States, where suitable habitats for northward movement are scarce. Cross-border
629 coordination, such as with Canada, could potentially increase the persistence of northern species,
630 aiding conservation goals (Schwartz et al., 2012; Vitt et al., 2010).

631   Fourth, our model presupposes that tree seeds, once deposited, can persist in the seed bank
632   through the entire duration of the 100-year simulation. Forest dynamic models frequently assume
633   indefinite seed longevity for computational ease and due to the absence of detailed seed longevity
634   data for most species (Botkin et al., 1972; Harald K. M. Bugmann & Solomon, 2000; Rasche et
635   al., 2012). However, empirical evidence suggests that most tree seeds do not survive more than a
636   year or two under typical field conditions (Davies et al., 2020; Mame et al., 2019; Nadarajan et al.,
637   2023). Therefore, the persistent seed bank assumed here could lead to an overestimation of
638   recruitment success, thereby potentially inflating the projected biomass for certain species. To
639   evaluate the impact of our assumption regarding long-term seed viability on our conclusions, we
640   conducted a series of simulations with a one-year seed bank duration under the SSP585 emission
641   scenario. The outcomes mirrored the patterns observed in Figures 2 and 4 (Figure S9). We interpret
642   this consistency to stem from the strong filtering effects of climate and light conditions on plant
643   growth and survival, such that these processes are the primary drivers of which species establish
644   and outweigh any effect of seed bank availability.

645   Lastly, our model does not account for the potential of phenotypic and genetic adaptations in
646   tree species, which might reduce extinction risk and the need for AM under climate change (Chown
647   et al., 2010; Nicotra et al., 2010). Short-term phenotypic changes, such as increased root-to-shoot
648   ratio for water efficiency (Nicotra et al., 2010), and long-term evolutionary adaptations are crucial
649   considerations (Alberto et al., 2013). The concept of assisted gene flow, moving locally-adapted
650   genes within species ranges, emerges as an additional strategy for dispersal-limited species,
651   warranting further investigation in future studies incorporating evolutionary dynamics (Aitken &
652   Bemmels, 2016; Kelly & Phillips, 2019; Young et al., 2020).

653

654   *Model applications to other settings*

655   Applying our approach in new geographic locations to evaluate conservation performance of
656   AM strategies requires data on species-specific physiological parameters (see Table.S1), which
657   might be available in the literature or the TRY dataset (Kattge et al., 2020), as well as data on
658   species occurrence and climatic tolerance traits. The European Alps are one candidate location for
659   implementing this framework to evaluate AM performance, because these parameters are available
660   for hundreds of European tree species (H. Bugmann, 1994). To inform management of climate-
661   threatened species in more data-poor locations, future research could focus on our broader take-
662   home messages of which species could be candidate functional types for AM (e.g., species
663   intolerant to fire, drought, or heat, depending on which environmental factors climate change is
664   impacting and how in a given location) and the effects of inter-specific competition on AM risks
665   and benefits.

666

667

668   **Open Research Statement**

669 The major code (novel) and example data to replicate the results in this paper are on the

670 GitHub repository: https://github.com/Yibiaozou/UCDavis_Forest_AM, which is also the

671 intended repository for permanent archive. Observation data and climatic data used in this paper

672 are already published and publicly available, with those items cited in this submission. Tree

673 observation data in year 2017 was downloaded from LEMMA

674 (https://lemmadownload.forestry.oregonstate.edu/) using the following query: [BA_GE_3,

675 ABAM_BA, ABGRC_BA, ABLA_BA, ABPRSH_BA, ACMA3_BA, ARME_BA, CHNO_BA,

676 PIEN_BA, PICO_BA, PIMO3_BA, PIPO_BA, PSME_BA, QUGA4_BA, TSHE_BA, TSME_BA,

677 CADE27_BA, PIJE_BA, PILA_BA, PIAL_BA, QUKE_BA, PIBA_BA]. For climatic data, we

678 used WorldClim version-2.1 [https://www.worldclim.org/data/cmip6/cmip6_clim30s.html]. For

679 burned-area data, we used observation from Williams et al. (2023) on Dryad

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681

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Biosketch

Yibiao Zou is broadly interested in global ecosystem ecology. This work represents a component of his undergraduate work at UC Davis on forest assisted migration. He now works on questions of alternative biome states and forest fragmentation in Crowther Lab, ETH Zurich (see Crowther Lab, https://crowtherlab.com/).

Author contributions: YZ, GAB and MLB, conceived the ideas; YZ conducted the simulations and analysed the data; and YZ led the writing with assistance from GAB, HDS, SS and MLB.