

Supporting Information for

**Climate change aggravates non-target effects of pesticides on  
dragonflies at continental scales**

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ECOLOGICAL APPLICATIONS

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## Section S1: Supplementary Design and Methodology

### Odonate data

The full raw dataset includes ~815 000 North American Odonata occurrence records. We first removed inadequate records from our primary dataset. Inadequate records were identified as those with incomplete information for species identification, year, or locality, inaccurate georeferenced points, and duplicate records. The United States of America (USA) was densely sampled compared to observation records of Northern Mexico and Northern Canada. We restricted the study extent because the pesticides data was only available in the USA, and because our assessment of range limit shifts benefits from including the most densely sampled locations for more accurate results. The following list enumerates 104 odonate species sampled across the USA between 1980 and 2018 which follow our criteria for quality observation records for inclusion in our analysis.

<i>Aeshna canadensis</i>	<i>Enallagma annexum</i>	<i>Lestes rectangularis</i>
<i>Aeshna constricta</i>	<i>Enallagma antennatum</i>	<i>Lestes unguiculatus</i>
<i>Aeshna eremita</i>	<i>Enallagma aspersum</i>	<i>Lestes vigilax</i>
<i>Aeshna interrupta</i>	<i>Enallagma basidens</i>	<i>Leucorrhinia frigida</i>
<i>Aeshna juncea</i>	<i>Enallagma boreale</i>	<i>Leucorrhinia glacialis</i>
<i>Aeshna palmata</i>	<i>Enallagma carunculatum</i>	<i>Leucorrhinia hudsonica</i>
<i>Aeshna sitchensis</i>	<i>Enallagma civile</i>	<i>Leucorrhinia intacta</i>
<i>Aeshna tuberculifera</i>	<i>Enallagma ebrium</i>	<i>Leucorrhinia proxima</i>
<i>Aeshna umbrosa</i>	<i>Enallagma exsulans</i>	<i>Libellula forensis</i>
<i>Amphiagrion abbreviatum</i>	<i>Enallagma geminatum</i>	<i>Libellula incesta</i>
<i>Amphiagrion saucium</i>	<i>Enallagma hageni</i>	<i>Libellula luctuosa</i>
<i>Anax junius</i>	<i>Enallagma signatum</i>	<i>Libellula pulchella</i>
<i>Argia apicalis</i>	<i>Enallagma vesperum</i>	<i>Libellula quadrimaculata</i>
<i>Argia fumipennis</i>	<i>Epitheca canis</i>	<i>Libellula saturata</i>
<i>Argia moesta</i>	<i>Epitheca cynosura</i>	<i>Macromia illinoiensis</i>
<i>Argia sedula</i>	<i>Epitheca princeps</i>	<i>Nehalennia irene</i>
<i>Argia tibialis</i>	<i>Epitheca spinigera</i>	<i>Ophiogomphus severus</i>
<i>Argia vivida</i>	<i>Erythemis simplicicollis</i>	<i>Pachydiplax longipennis</i>
<i>Basiaeschna janata</i>	<i>Hagenius brevistylus</i>	<i>Pantala flavescens</i>
<i>Boyeria vinosa</i>	<i>Hetaerina americana</i>	<i>Pantala hymenaea</i>
<i>Calopteryx aequabilis</i>	<i>Ischnura cervula</i>	<i>Perithemis tenera</i>
<i>Calopteryx maculata</i>	<i>Ischnura hastata</i>	<i>Phanogomphus exilis</i>
<i>Celithemis elisa</i>	<i>Ischnura perparva</i>	<i>Phanogomphus lividus</i>
<i>Celithemis eponina</i>	<i>Ischnura posita</i>	<i>Phanogomphus spicatus</i>
<i>Chromagrion conditum</i>	<i>Ischnura verticalis</i>	<i>Plathemis lydia</i>
<i>Coenagrion resolutum</i>	<i>Ladona julia</i>	<i>Rhionaeschna californica</i>
<i>Cordulegaster maculata</i>	<i>Lestes congener</i>	<i>Rhionaeschna multicolor</i>
<i>Cordulia shurtleffi</i>	<i>Lestes disjunctus</i>	<i>Somatochlora franklini</i>
<i>Didymops transversa</i>	<i>Lestes dryas</i>	<i>Somatochlora minor</i>
<i>Dorocordulia libera</i>	<i>Lestes forcipatus</i>	<i>Somatochlora</i>
<i>Dromogomphus spinosus</i>	<i>Lestes inaequalis</i>	<i>semicircularis</i>

*Somatochlora walshii*  
*Stylogomphus albistylus*  
*Sympetrum corruptum*  
*Sympetrum costiferum*

*Sympetrum danae*  
*Sympetrum internum*  
*Sympetrum obtrusum*  
*Sympetrum pallipes*

*Sympetrum rubicundulum*  
*Sympetrum semicinctum*  
*Sympetrum vicinum*  
*Tramea lacerata*

### Model information and statements

We report the full base model statement below as executed with the *MCMCglmm* R package, including the priors, and the model of trait evolution to account for phylogeny. Prior structure followed standard practice associated with a binary response variable, and a categorical random variable. The family “threshold” was selected because of the binary nature of the data.

```
Aphylo <- vcv(phylogeny, model = "Brownian", corr = T)
Ainv <- inverseA(phylogeny, nodes = "TIPS", scale = F)$Ainv
```

```
prior <- list(R=list(V=1,fix=1),
             G=list(G1=list(V=1,nu=0.02)))
```

```
MCMCglmm(Persistence ~ Pesticides + Temperature + Precipitation + Land use + Sampling
intensity, random = ~ Species, ginverse = list(species = Ainv), family = "threshold", prior =
prior, DIC = T, nitt = 200000, thin = 50, burnin = 20000, data)
```

Further, we tested whether species that expand their range more strongly are also expected to persist or decline between a historical and a recent time period.

```
MCMCglmm(Persistence ~ Range expansion, random = ~ Species, ginverse = list(species =
Ainv), family = "threshold", prior = prior, DIC = T, nitt = 100000, thin = 50, burnin = 10000,
data)
```

### **Section S2: Supplementary Acknowledgements**

We sincerely thank data contributors who have made this project possible. The majority of observation records were downloaded from two online aggregators of databases, GBIF<sup>1</sup> and Canadensys<sup>2</sup>. We supplemented the dataset with data originating from other institutions including OdonataCentral<sup>3</sup>, the Ontario Odonata Atlas Database<sup>4</sup>, a repository of seven entomological collections of Québec<sup>5</sup>, and entomological collections of the Royal Ontario Museum, the Royal BC Museum, and the California Academy of Sciences. The following list enumerates all institutions within our full raw dataset, ordered by the number of records contributed.

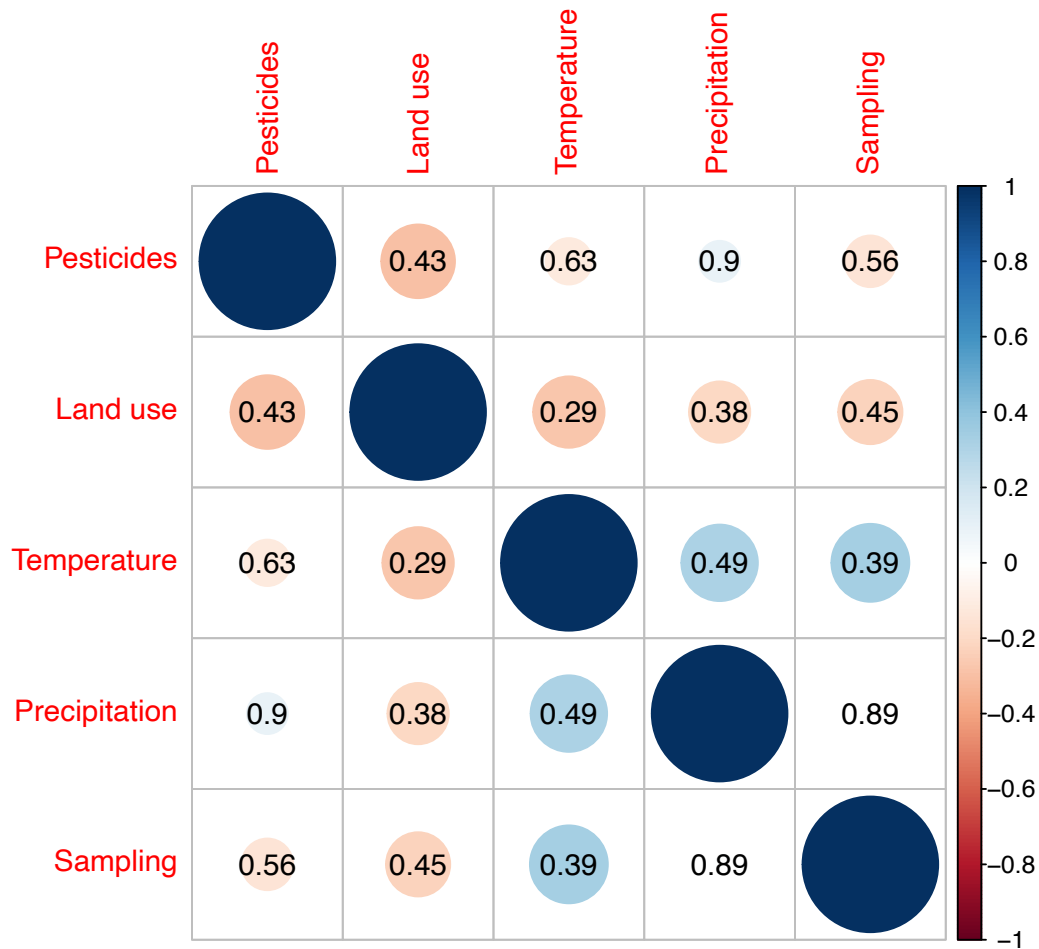
<u>Institution Name</u>	<u>Number of records contributed</u>
Odonata Central	251269
iNaturalist Research-grade Observations	137000
Ontario Odonata Atlas Database	98309

Ouellet-Robert entomological collection (QMOR)	81132
NMNH Extant Specimen Records	51000
Université de Montréal Biodiversity Centre	31980
Royal BC Museum	30770
BugGuide - Identification, Images, & Information For Insects, Spiders & Their Kin For the United States & Canada	17000
Royal Ontario Museum	14510
University of British Columbia - Spencer Entomological Collection (UBCZ)	14257
Illinois Natural History Survey Insect Collection	11000
C.A. Triplehorn Insect Collection (OSUC), Ohio State University	8000
Snow Entomological Museum Collection	8000
Odonata de Veracruz	6000
Collection entomologique de l'Université Laval (ULQC)	5149
Cleveland Museum of Natural History.	4000
Odonates des Antilles françaises	4000
Entomology Division, Yale Peabody Museum	3000
Insecta of Costa Rica (INBio)	3000
International Barcode of Life project (iBOL)	3000
Odonata de la huasteca potosina (insecta)	3000
Texas A&M University Insect Collection	3000
California Academy of Sciences	2615
Insectarium de Montréal (IMQC)	2004
CAS Entomology (ENT)	2000
Diversidad de ocho grupos de insecta (Odonata, Lycidae, Phengodidae, Lampyridae, Cantharidae, Cerambycidae, Syrphidae y Vespidae) en tres regiones con bosque tropical caducifolio en México	2000
UAM Insect Collection (Arctos)	2000
Lyman Entomological Museum (LEMQ)	1921
University of Guelph Insect Collection (DEBU)	1738
Espace pour la vie (CIQ)	1641
Centre for Biodiversity Genomics - Canadian Specimens	1000
Recent Invertebrates Specimens	1000
Stuart M. Fullerton Collection of Arthropods (UCFC), University of Central Florida	1000
University of Alberta Freshwater Invertebrate Collection (UAFIC)	989
Reconocimiento de la biodiversidad de la Reserva de la Biósfera Calakmul: Odonata, psocóptera y díptera acuáticos (Insecta)	858
Field Museum of Natural History (Zoology) Insect, Arachnid and Myriapod Collection	613
naturgucker	607

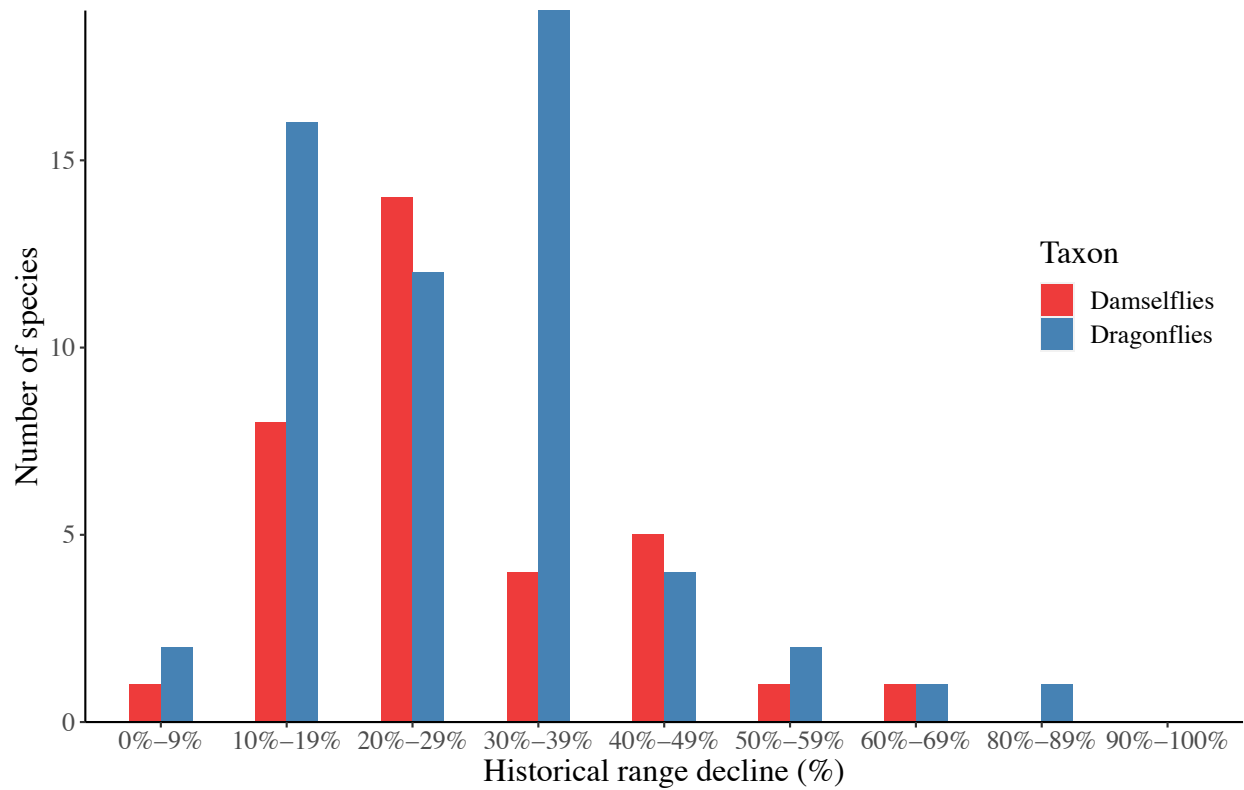
Diversidad de grupos selectos de vertebrados (Reptilia, Amphibia) e insectos (Lepidoptera: Papilionoidea y Hesperioidea; Odonata; Diptera: Bombyliidae) en el Valle de Cuatrociénegas y Sierra de la Madera, Coahuila, México	533
Geographically tagged INSDC sequences	487
Entomology Collection at the Natural History Museum of Utah	464
Bishop's University Insect Collection (BUIC)	456
CNIN/Tipos Odonata	225
University of Alberta E. H. Strickland Entomological Museum (UASM)	218
Insectarium René-Martineau (IRM)	214
UAM Insect Observations (Arctos)	176
Diversidad y distribución geográfica de las especies de culícidos de importancia médica en la región centro-occidental de México	164
A synopsis of the Neotropical genus <i>Protoneura</i> (Odonata: Coenagrionidae)	140
New species of the damselfly genus <i>Argia</i> from Mexico, Central America and Ecuador with an emphasis on Costa Rica (Insecta: Odonata: Coenagrionidae)	139
Colorado Plateau Museum of Arthropod Biodiversity	132
Macaulay Library Audio and Video Collection	132
Paleobiology Database	124
Questagame weekly feed	118
Fauna acuática de importancia ecológica (crustáceos, insectos y peces) de la cuenca del río Moctezuma Querétaro-Hidalgo	99
CHAS Entomology Collection (Arctos)	91
UPRM Invertebrate Collection	91
Computarización de la Colección Nacional de insectos Dr. Alfredo Barrera Marín del Museo de Historia Natural de la Ciudad de México	67
Invertebrate Paleontology Division, Yale Peabody Museum	49
Inventaire entomologique standardisé des ZNIEFF de Martinique, protocole utilisé en 2014 et 2015	48
Ontario BioBlitz Species Records	48
Inventory and BioBlitz Records from rare Charitable Research Reserve	45
Biodiversity Institute of Ontario	44
Données photographiques validées de la galerie du forum "Le Monde des Insectes"	42
CU Invertebrate Paleontology	40
Base de datos de la Colección zoológica del Instituto de Investigación de zonas desérticas de la Universidad Autónoma de San Luis Potosí (BDCZIID-UASLP)	35
Inventaire entomologique standardisé des ZNIEFF de Martinique, protocole utilisé de 2011 à 2013	35
Colección Macroinvertebrados Acuáticos Universidad Católica de Oriente	33
Ville de Trois-Rivières	32
Macroinvertebrados y perifiton pertenecientes a cuatro regiones de Colombia	29
Atlantic Reference Centre (ARC) Museum of Canadian Atlantic Organisms - Invertebrates and Fishes Data	29

KNWR Entomology Collection	21
Étude entomologique des forêts publiques de Martinique, pour l'ONF	20
USGS Patuxent Wildlife Research Center Seabirds Compendium	19
Caracterización de fauna y flora para el establecimiento de límites funcionales de humedales en tres ventanas piloto: Ciénaga de la Virgen, Ciénaga Zapatosa y Complejo de humedales Paz de Ariporo - Hato Corozal	13
Natural History Museum Rotterdam (NL) - Insecta collection	11
Rapid Assessment Program (RAP) Biodiversity Survey Database	11
Paleobiology Database	10
Colección Limnológica del Chocó	8
Museum of Southwestern Biology, Division of Arthropods	8
Borror Lab of Bioacoustics (BLB), Ohio State University	7
Colección Entomológica de Piedras Blancas	7
Entomological Collections (NHRS), Swedish Museum of Natural History (NRM)	6
Harold W. Manter Laboratory of Parasitology Collection	6
VMNH Invertebrate Paleontology	6
BoBO - Botanic Garden and Botanical Museum Berlin-Dahlem Observations	5
<i>Cordulegaster virginiae</i> sp. nov. from Mexico, including a comparison with <i>C. diadema</i> Selys, 1868, and a redescription of its larva (Odonata: Cordulegastridae)	5
Arizona State University Hasbrouck Insect Collection	3
Australian National Insect Collection	3
Colección de Referencia de Macroinvertebrados Bentónicos del Museo de Ciencias de la Universidad El Bosque	3
Entomology at ZMUC, Natural History Museum of Denmark	3
Essig Museum of Entomology	3
The genus <i>Heteragrion</i> (Odonata: Zygoptera) in Northwestern Colombia, with the description of <i>Heteragrion tatama</i> sp. nov.	3
UCMC_Entomology	3
Données de type contact de Guadeloupe	2
Estonian Museum of Natural History	2
Museum of Comparative Zoology, Harvard University	2
<i>Erpetogomphus oxybelis</i> sp. nov. from Veracruz, Mexico (Odonata: Gomphidae)	1
Natusfera Citizen Science Observation Dataset	1
Observations naturalistes et collection entomologique de Julien TOUROULT	1
Odonata del Museo de Entomología de la Universidad del Valle	1
<i>Phyllogomphoides enriquei</i> (Odonata: Gomphidae) a new species from Mexico	1
USGS PWRC - Native Bee Inventory and Monitoring Lab (BIML)	1
Vegetación vascular terrestre, entomofauna y macrofauna de la Isla Cayo Serrana durante la Expedición Seaflower 2016 - Proyecto Colombia BIO	1

Section S3: Supplementary Figures S1 – S8



**Figure S1:** Pearson correlation coefficients between all predictor variables likely to impact changes in odonate persistence. The criteria of  $p\text{-value} < 0.05$  was used to determine whether potential correlations between variables were significant. P-values of the correlation test are shown for each pairwise test. P-values were calculated with the *cor* base function in R statistical software.



**Figure S2:** Summary histogram ordered by category of decline in 104 species in the United States of America. We show the percentage of quadrats lost in recent years (2008-2018) compared to historical presences (1980-2002).

Figure S3, A

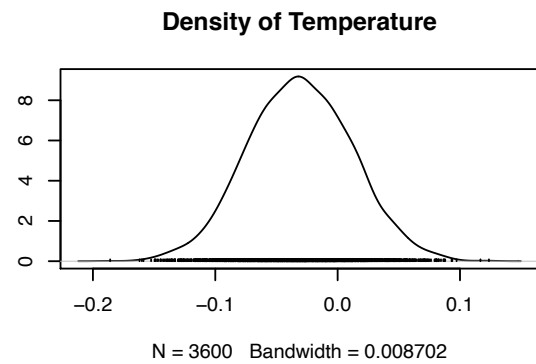
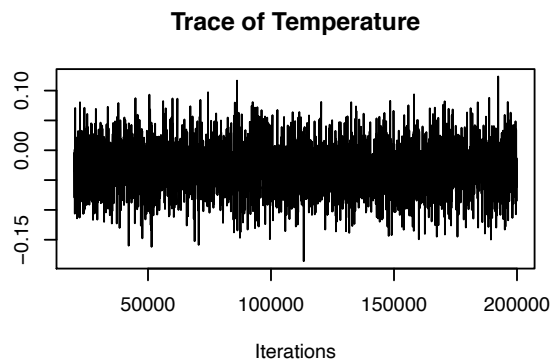
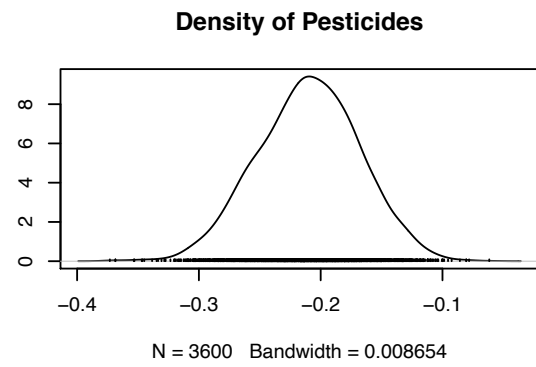
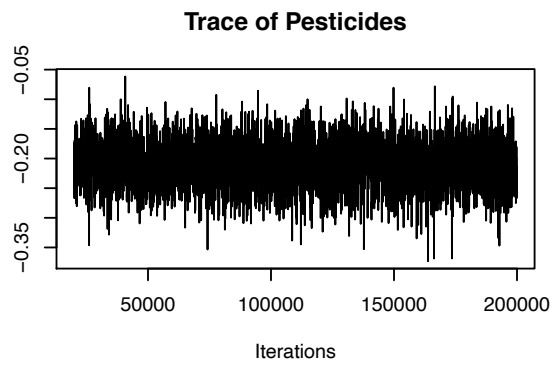
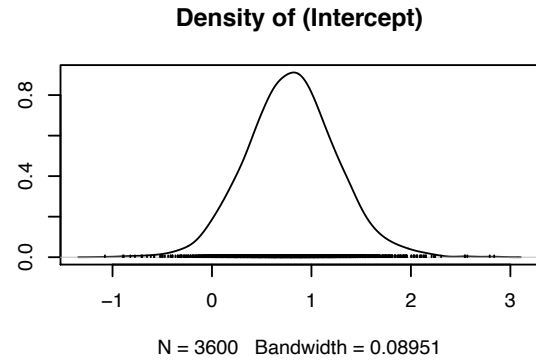
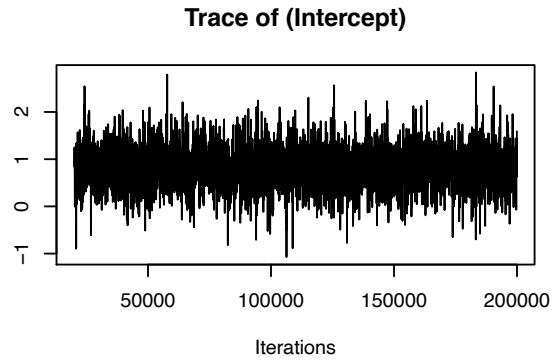


Figure S3, B

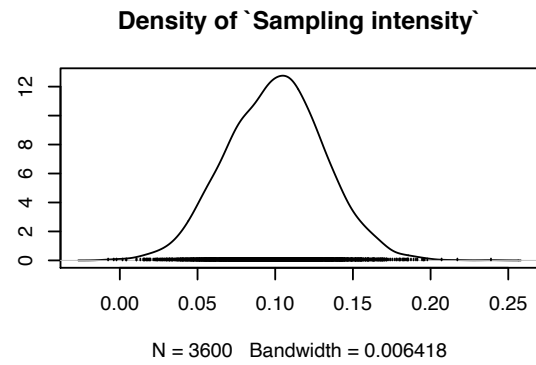
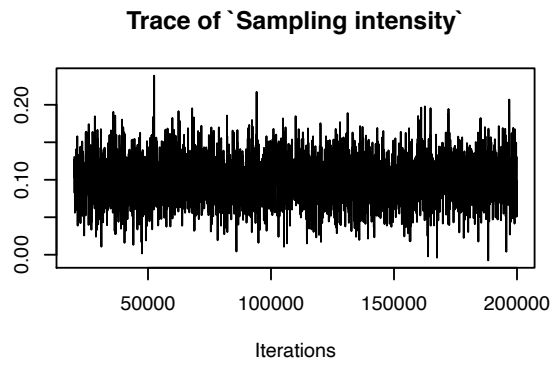
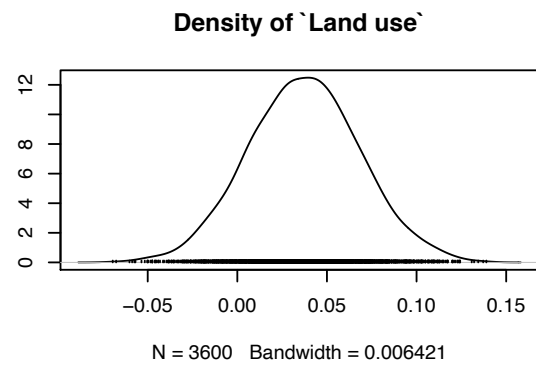
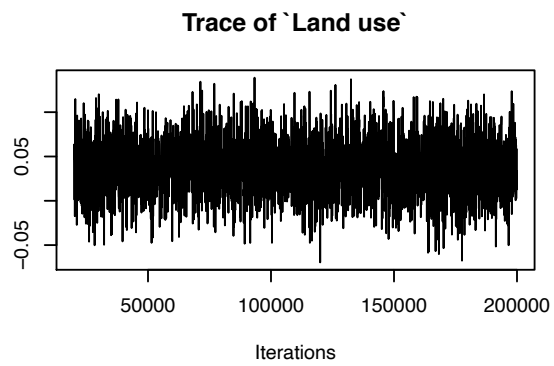
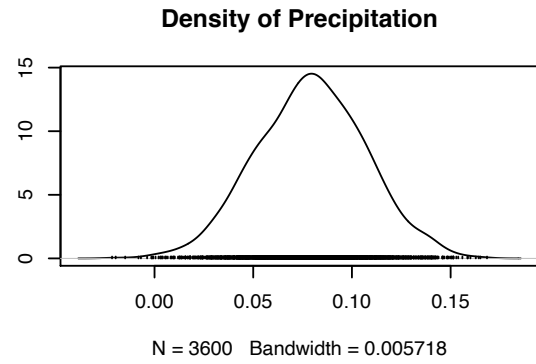
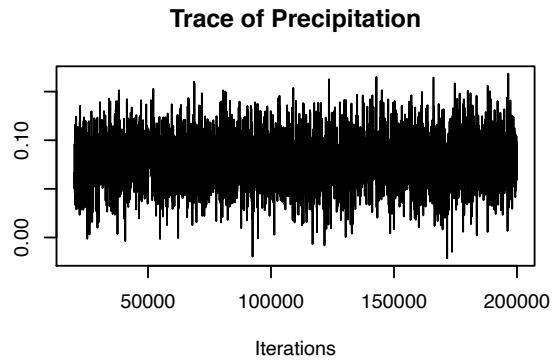
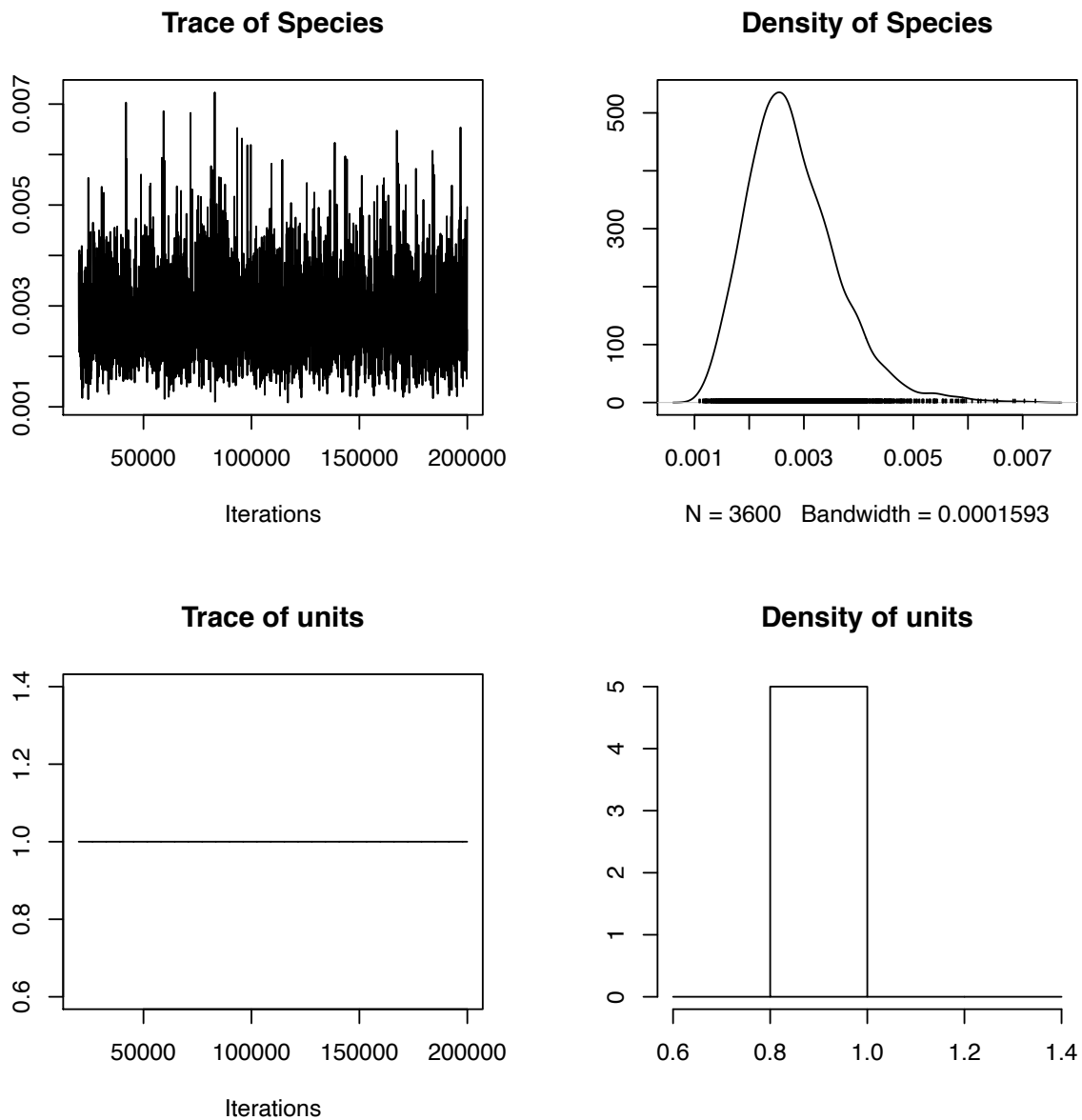


Figure S3, C



**Figure S3:** Panels A, B and C show the trace and density estimates of Model 1, a phylogenetic mixed effects model using global change variables to explain odonate persistence in the United States of America, with species as a random effect. 200 000 iterations were run to produce these results. These plots verify model convergence and absence of autocorrelation within the explanatory variables.

Figure S4, A

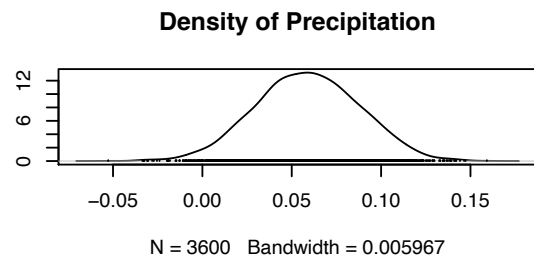
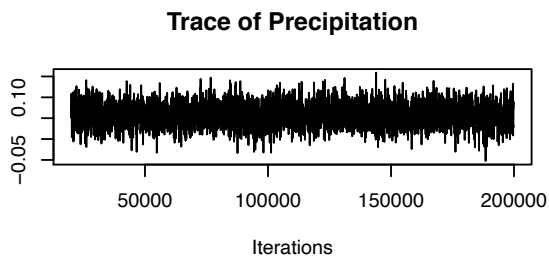
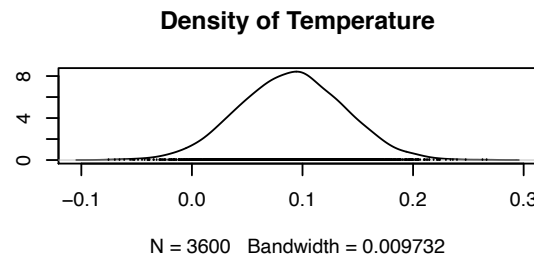
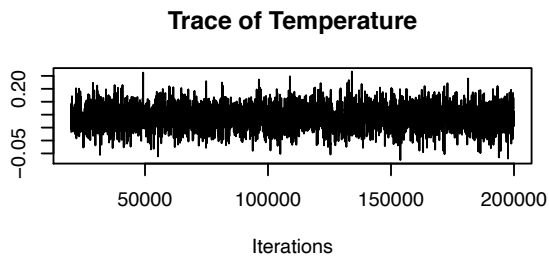
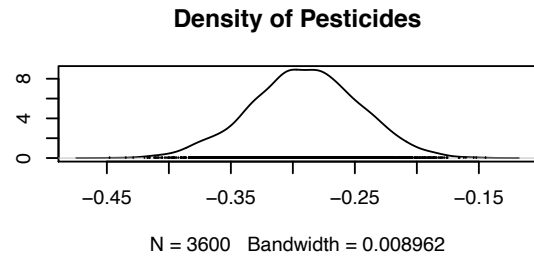
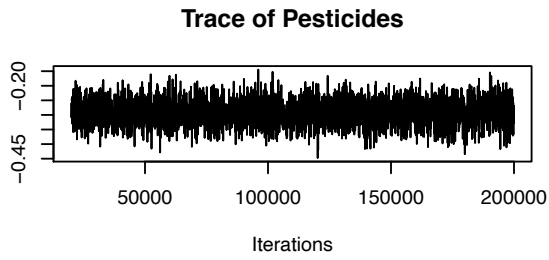
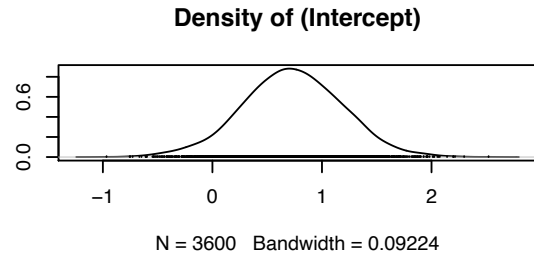
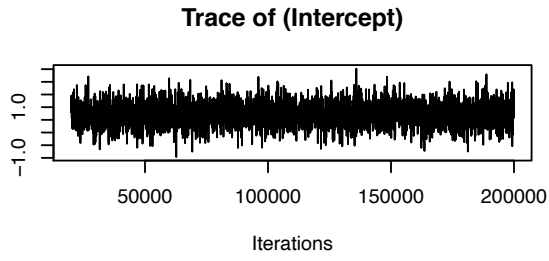


Figure S4, B

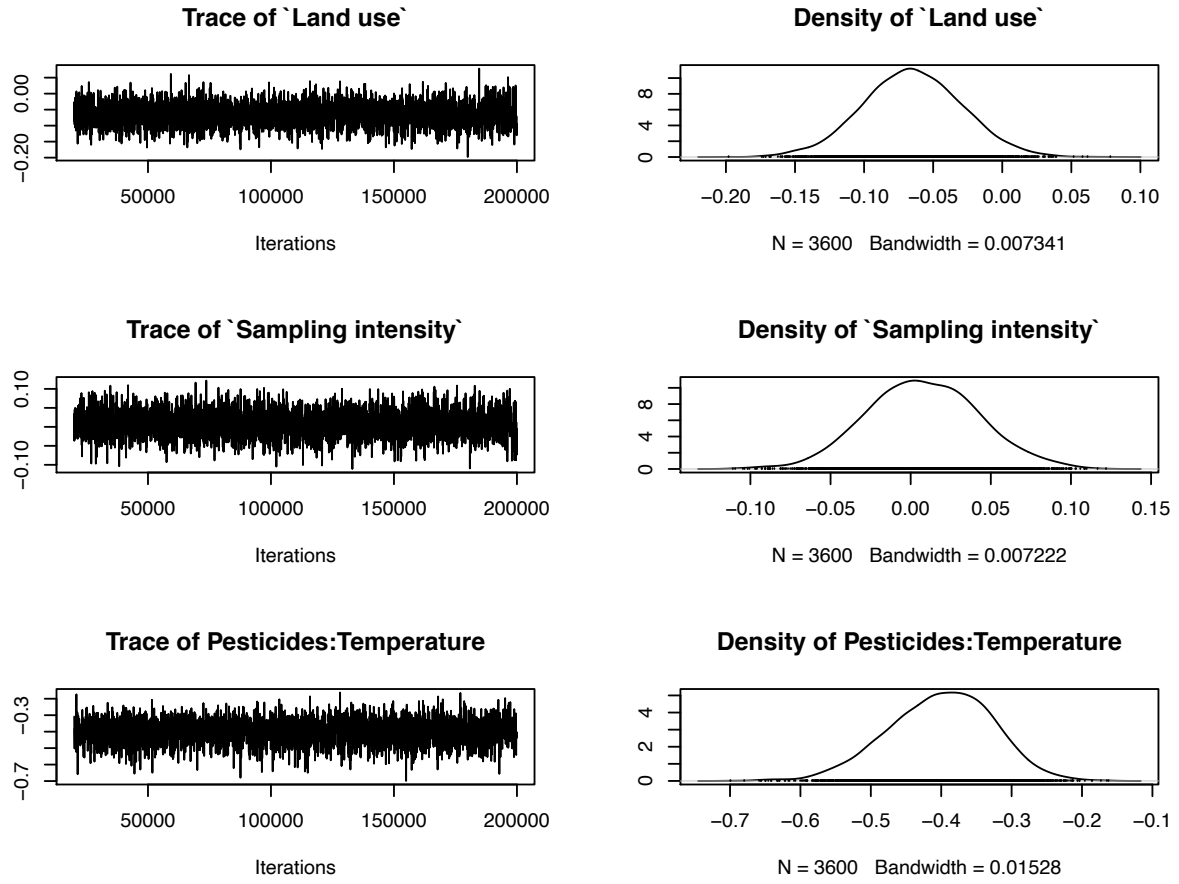
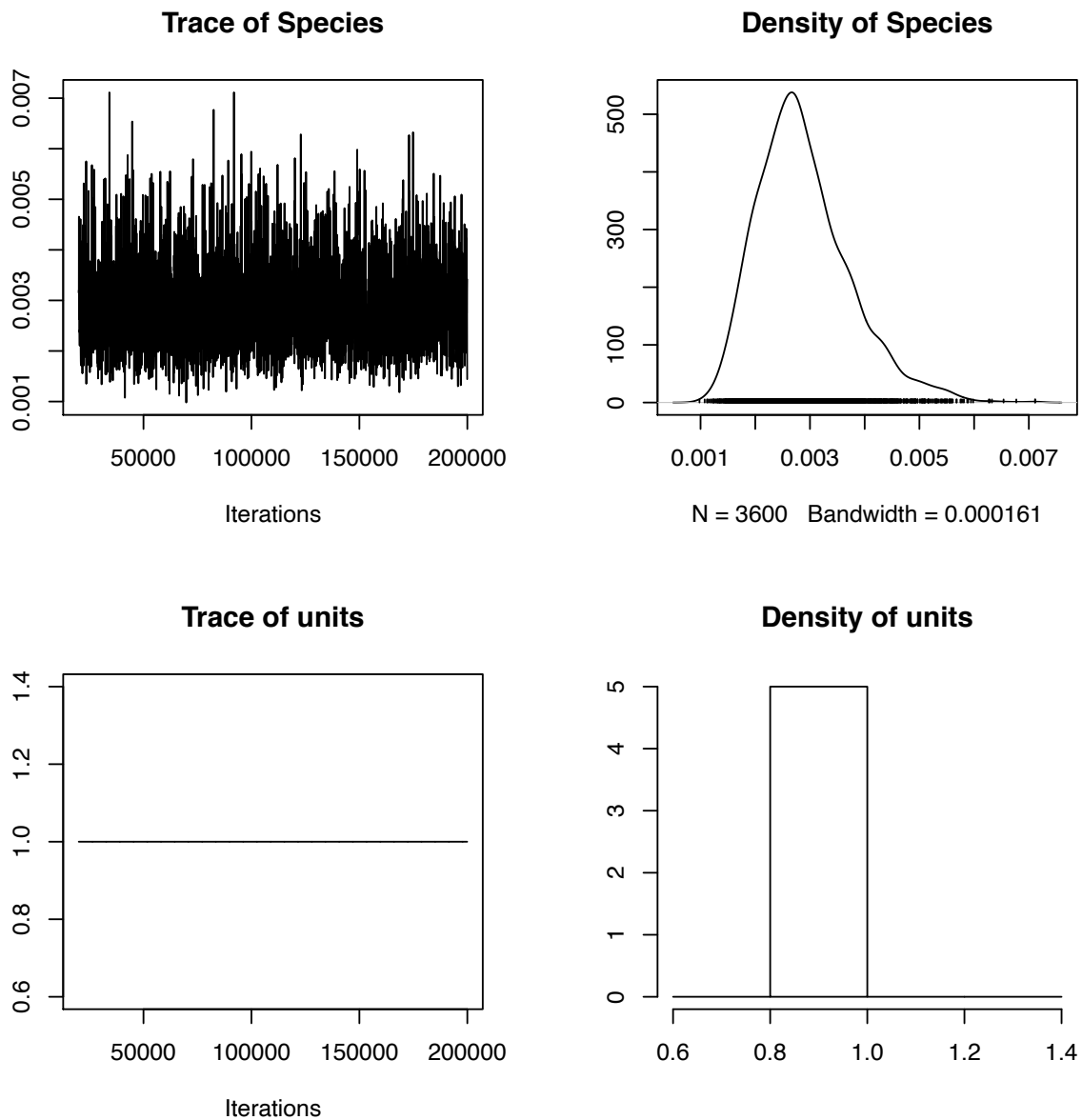


Figure S4, C



**Figure S4:** Panels A, B and C show the trace and density estimates of Model 2, a phylogenetic mixed effects model using global change variables to explain odonate persistence in the United States of America, with species as a random effect. 200 000 iterations were run to produce these results. These plots verify model convergence and absence of autocorrelation within the explanatory variables.

Figure S5, A

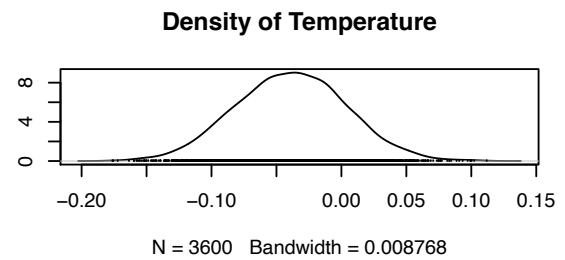
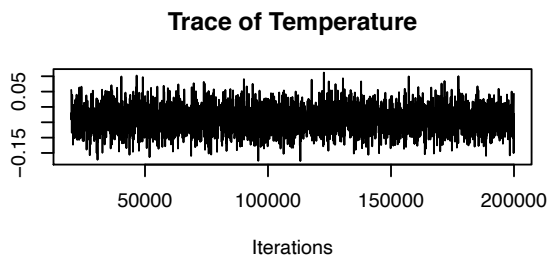
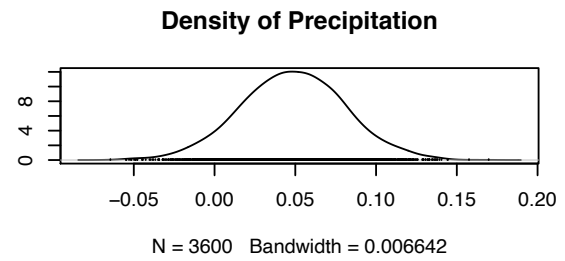
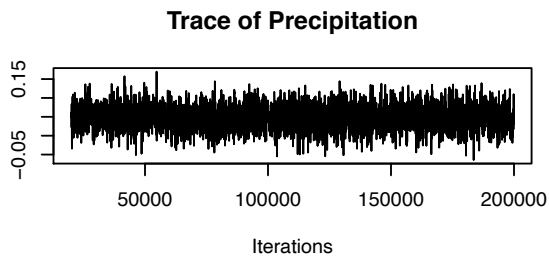
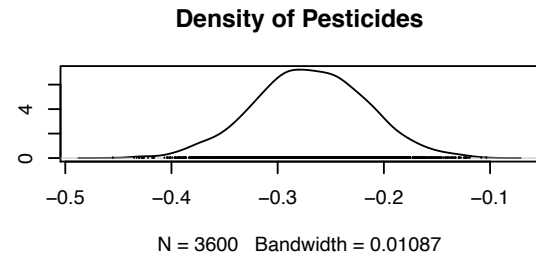
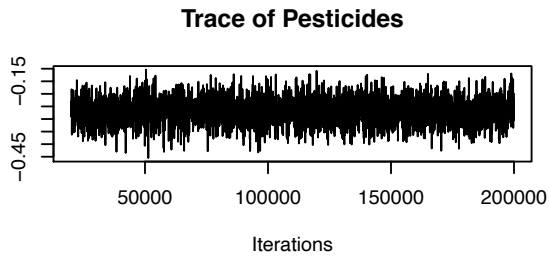
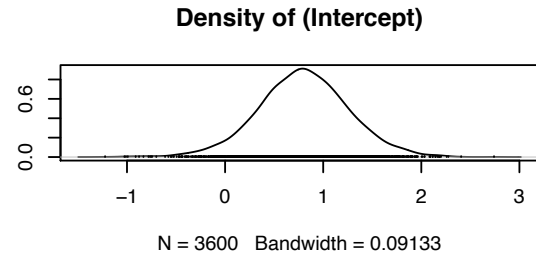
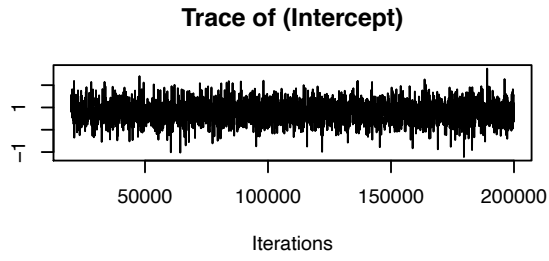


Figure S5, B

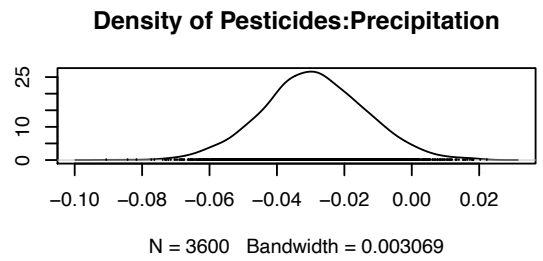
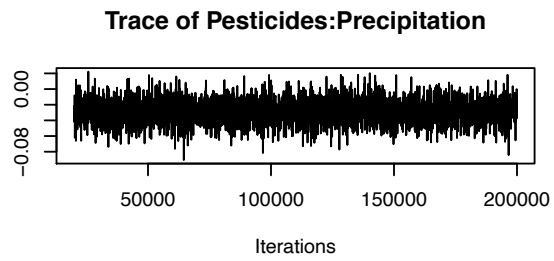
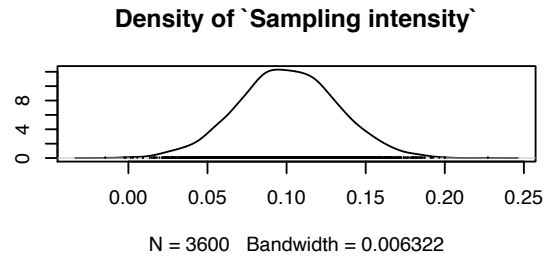
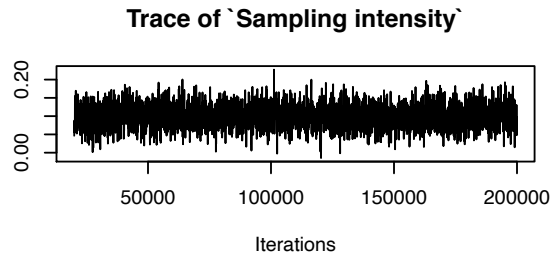
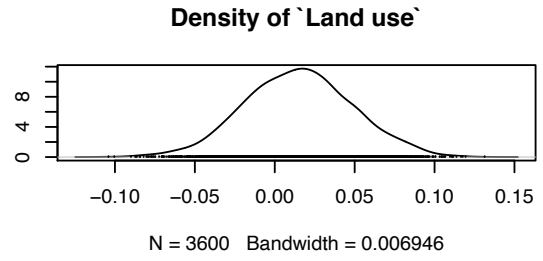
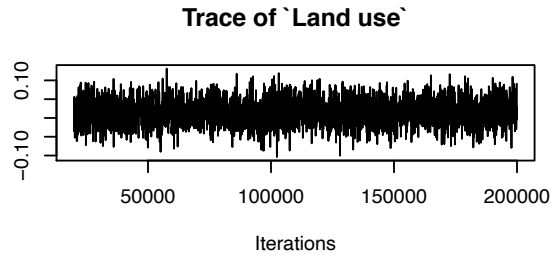
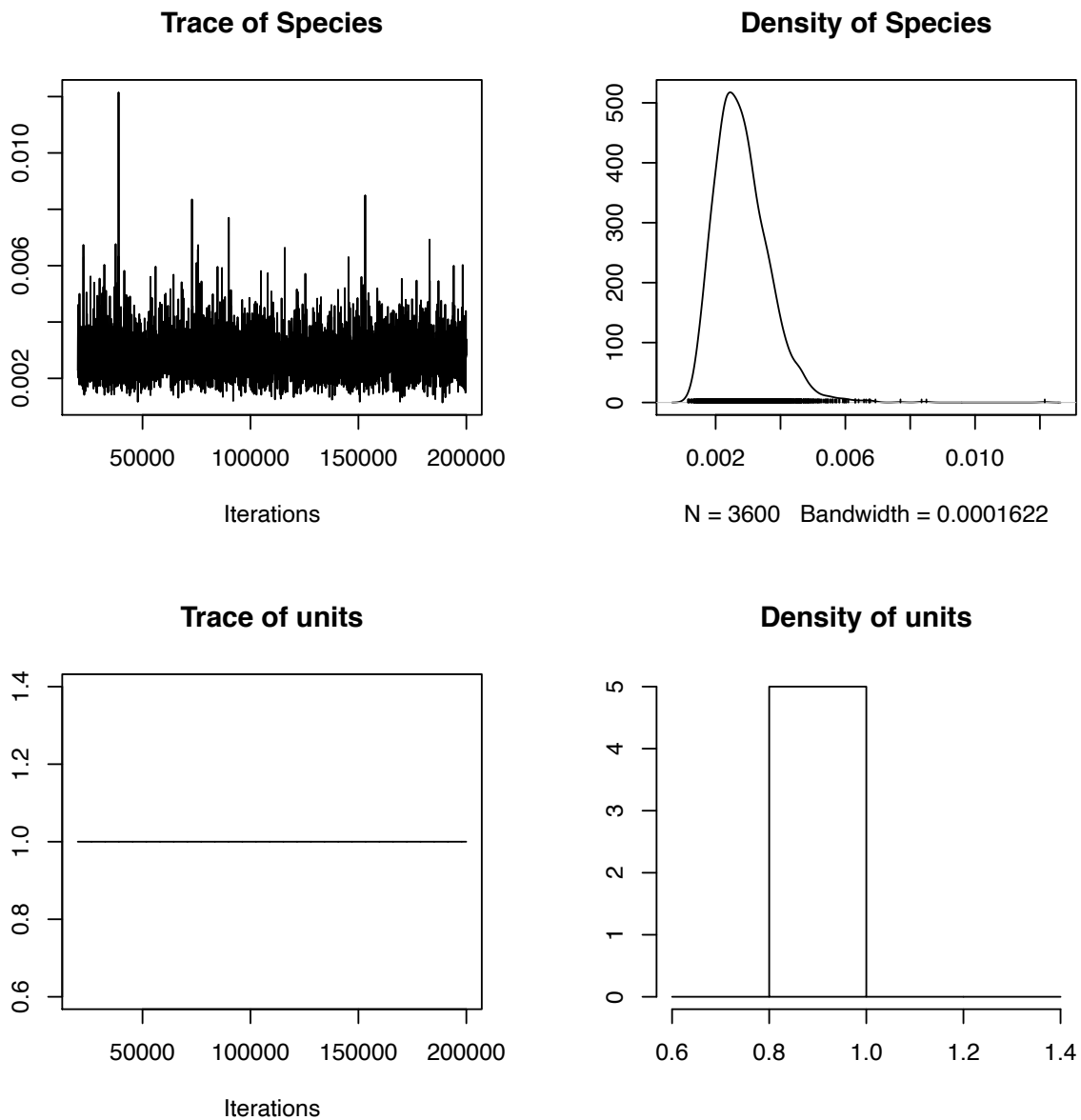


Figure S5, C



**Figure S5:** Panels A, B and C show the trace and density estimates of Model 3, a phylogenetic mixed effects model using global change variables to explain odonate persistence in the United States of America, with species as a random effect. 200 000 iterations were run to produce these results. These plots verify model convergence and absence of autocorrelation within the explanatory variables.

Figure S6, A

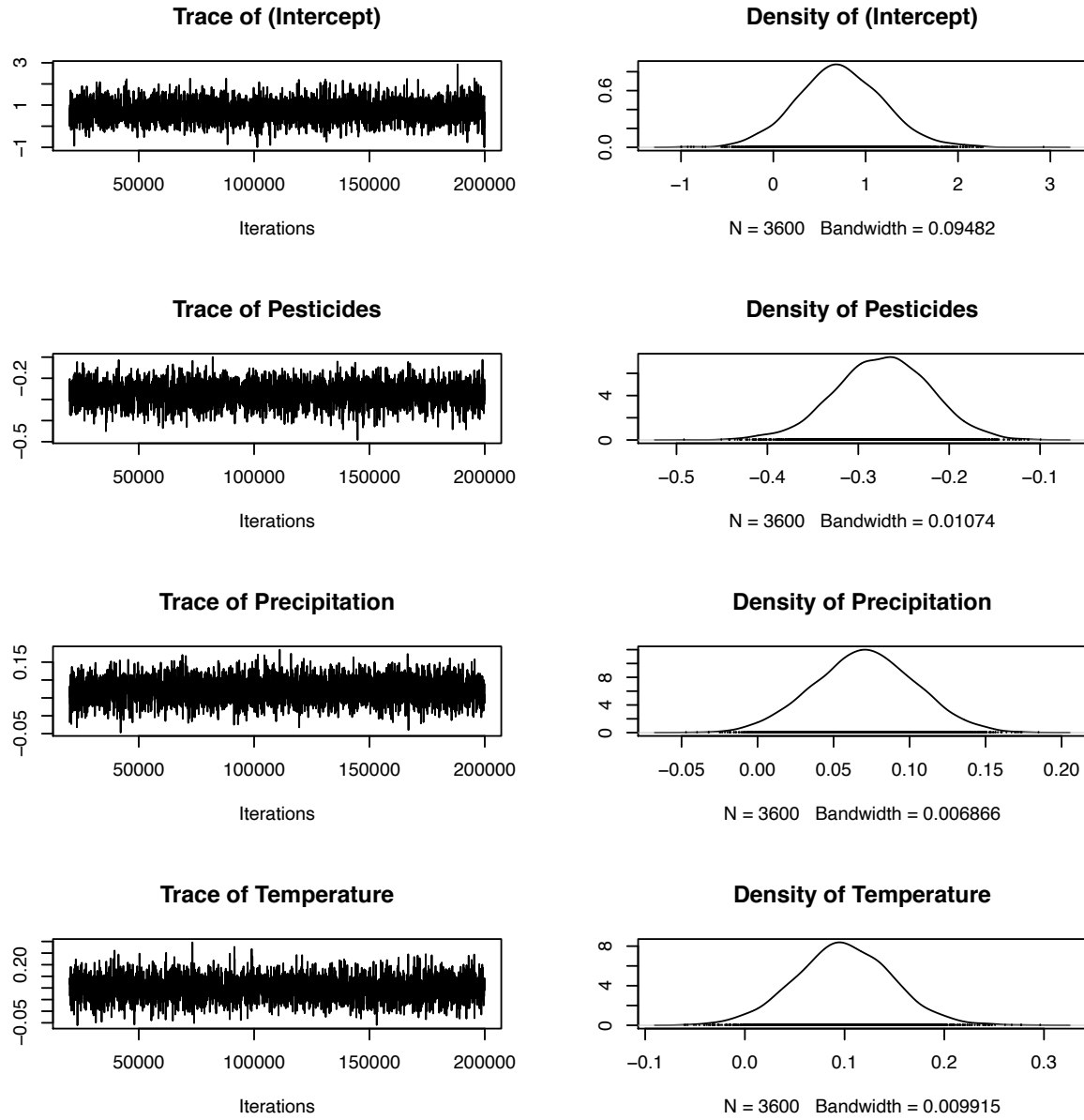


Figure S6, B

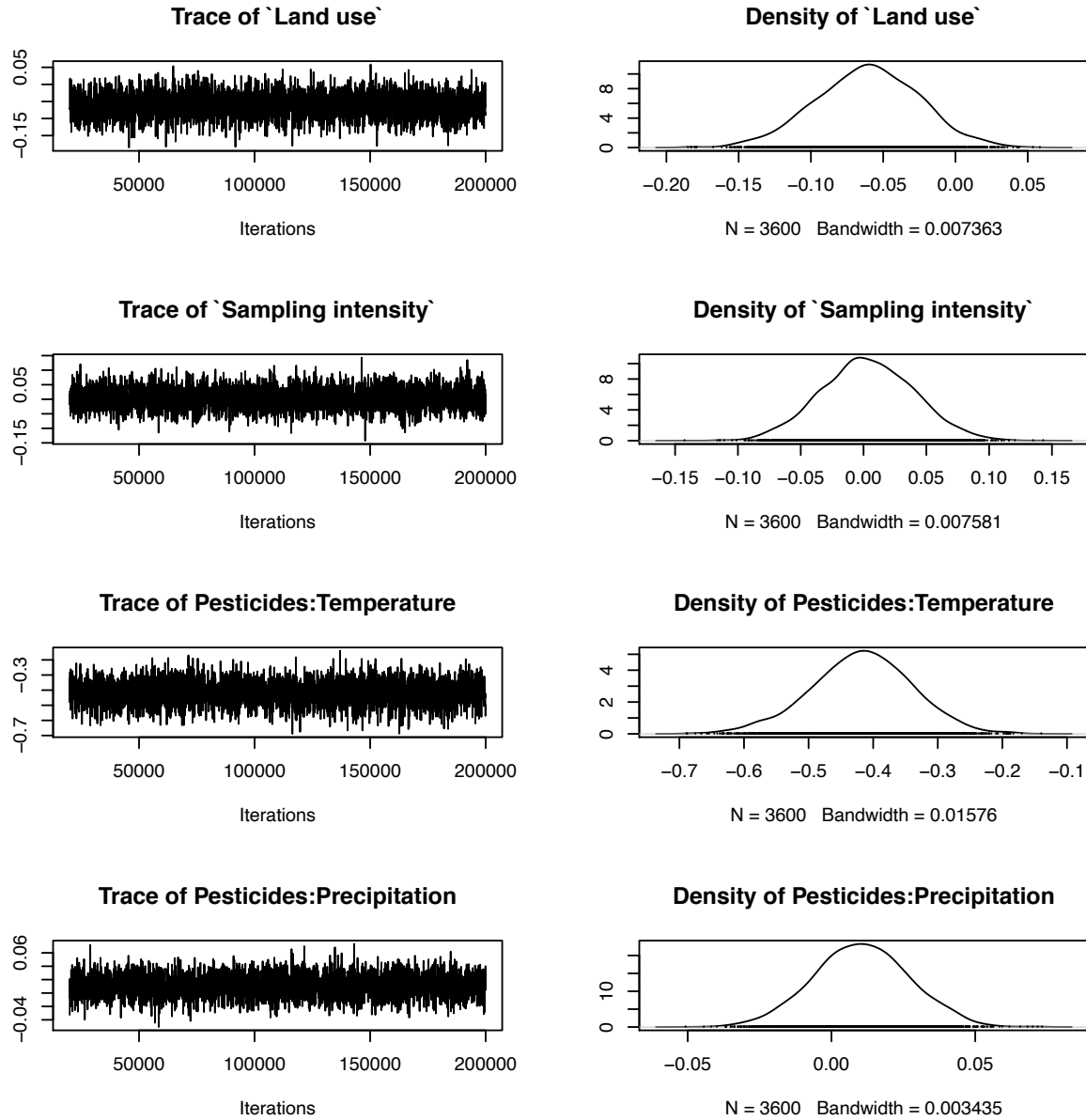
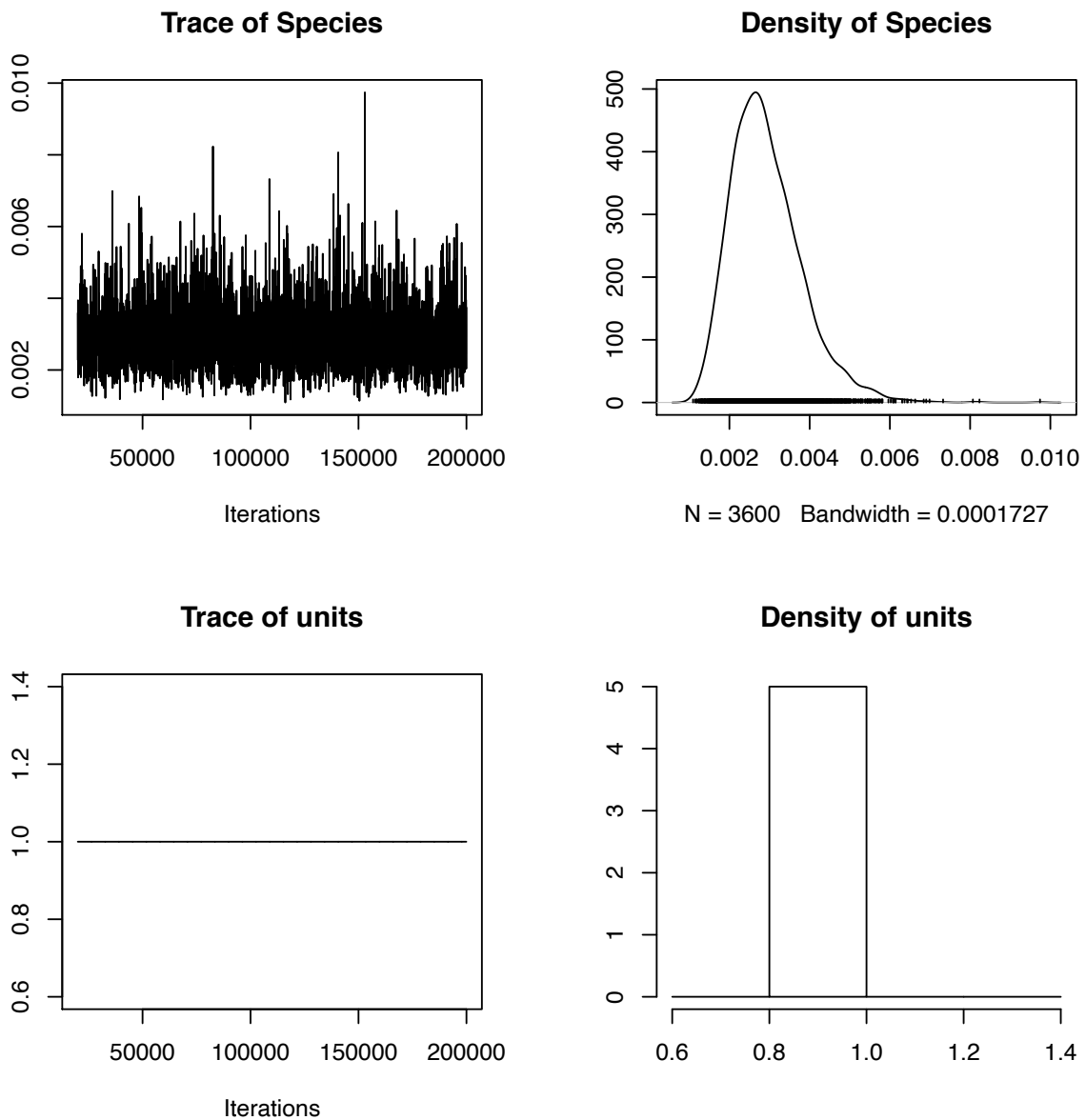


Figure S6, C



**Figure S6:** Panels A, B and C show the trace and density estimates of Model 4, a phylogenetic mixed effects model using global change variables to explain odonate persistence in the United States of America, with species as a random effect. 200 000 iterations were run to produce these results. These plots verify model convergence and absence of autocorrelation within the explanatory variables.

Figure S7, A

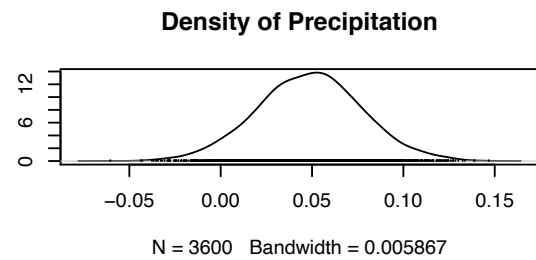
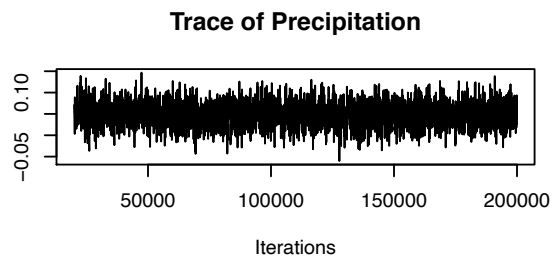
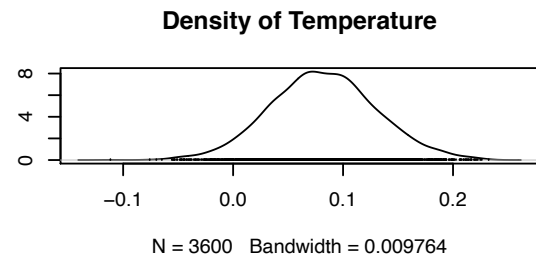
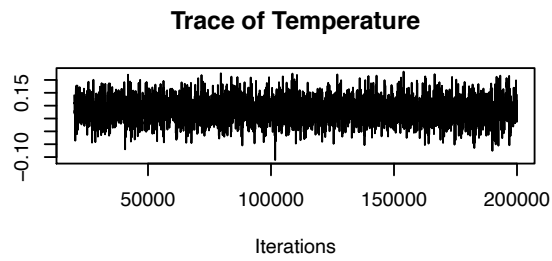
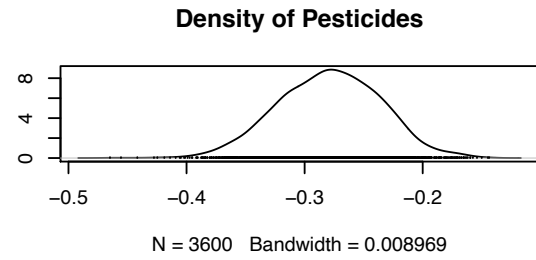
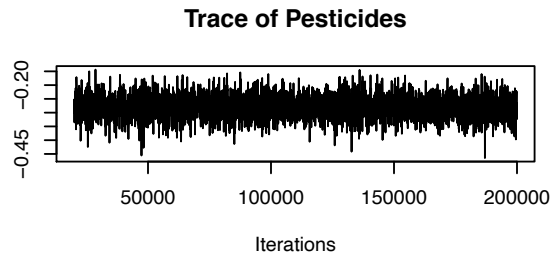
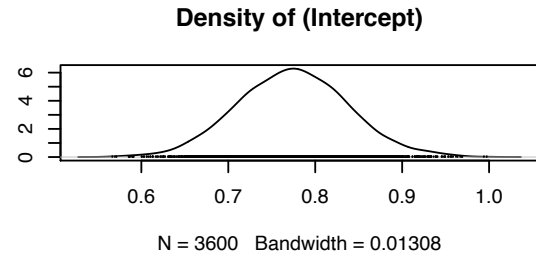
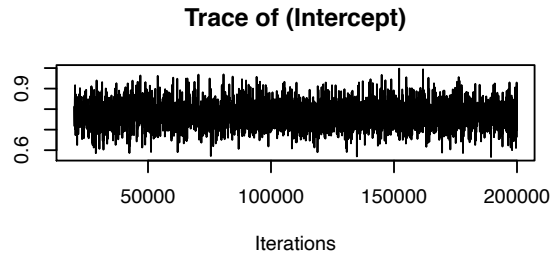


Figure S7, B

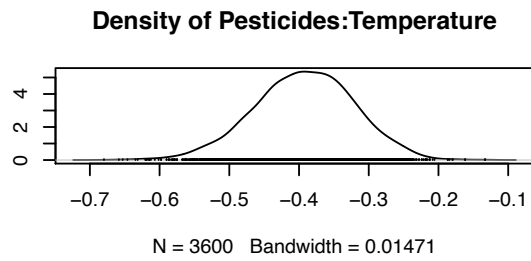
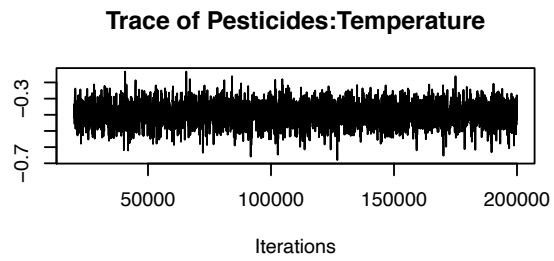
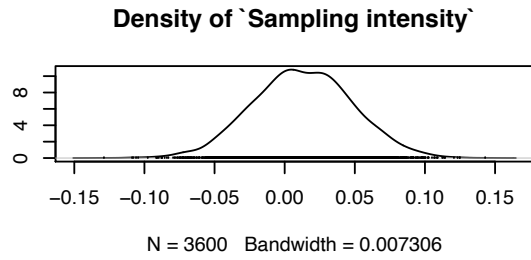
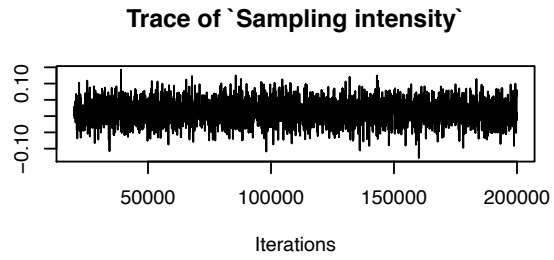
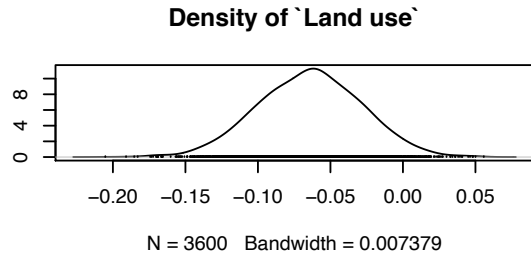
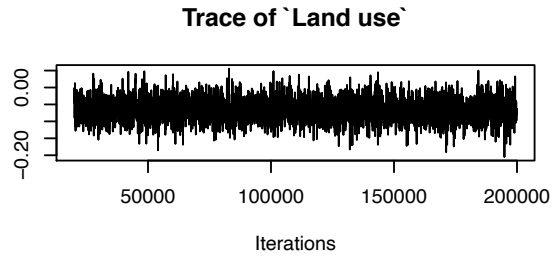
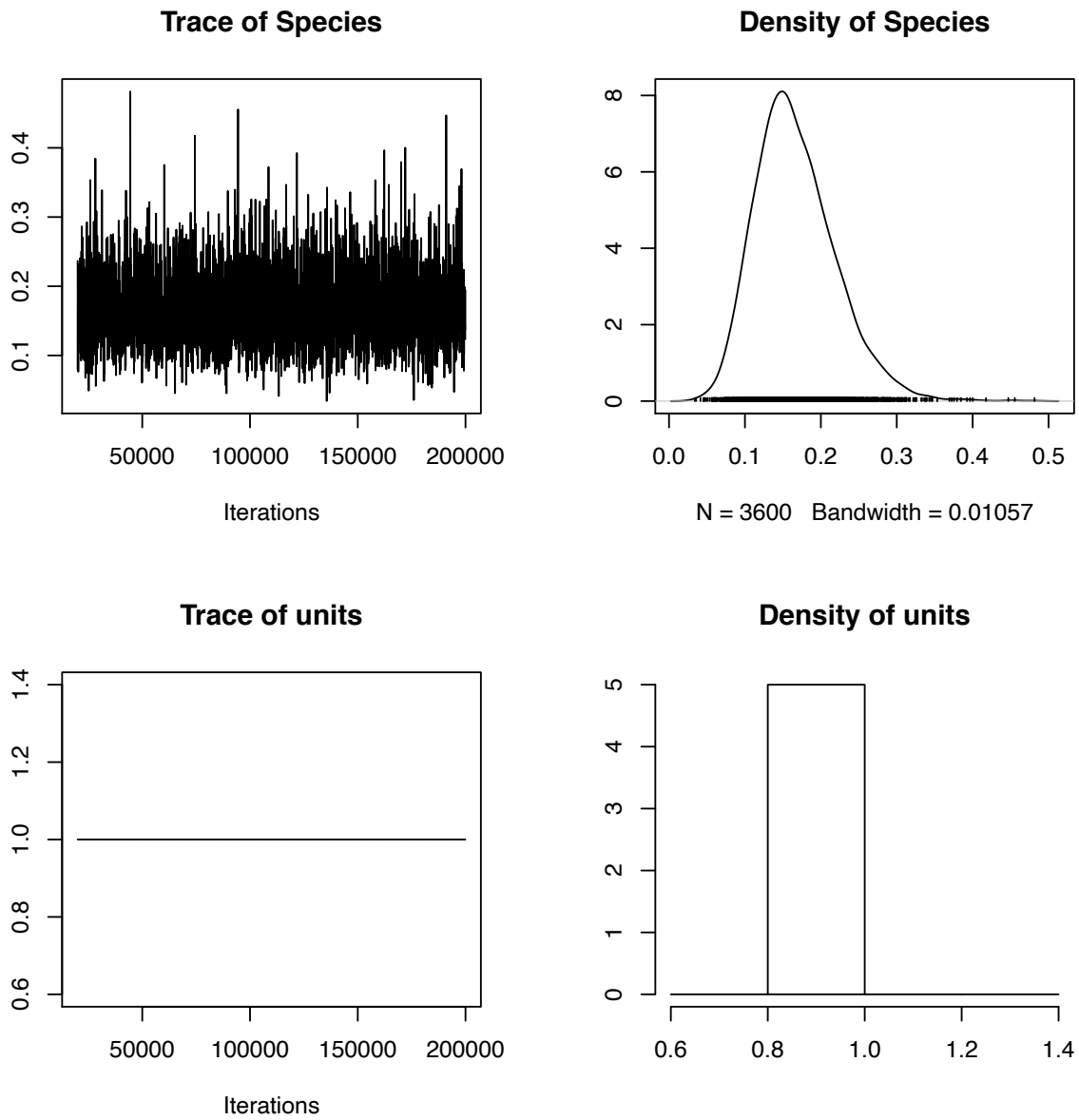


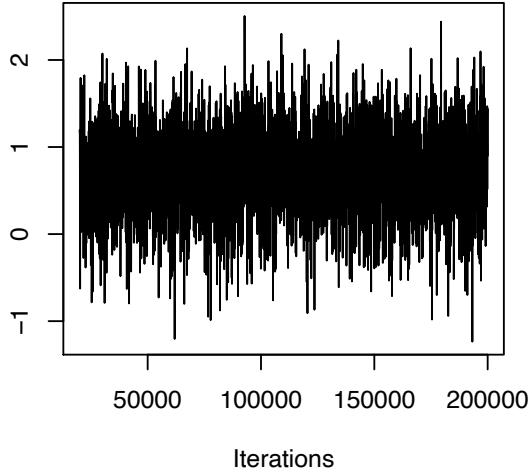
Figure S7, C



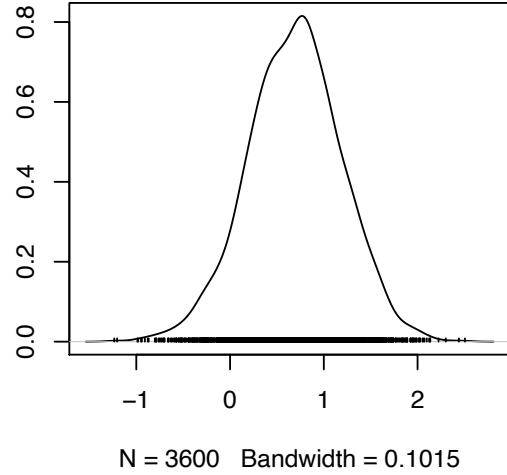
**Figure S7:** Panels A, B and C show the trace and density estimates of Model 5, a non-phylogenetic mixed effects model using global change variables to explain odonate persistence in the United States of America, with species as a random effect. 200 000 iterations were run to produce these results. These plots verify model convergence and absence of autocorrelation within the explanatory variables.

Figure S8, A

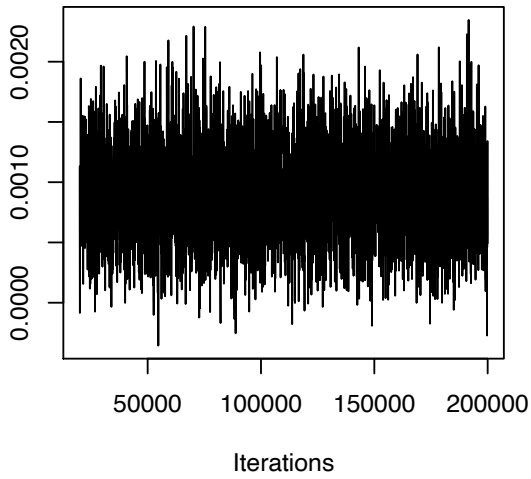
**Trace of (Intercept)**



**Density of (Intercept)**



**Trace of Range\_expansion**



**Density of Range\_expansion**

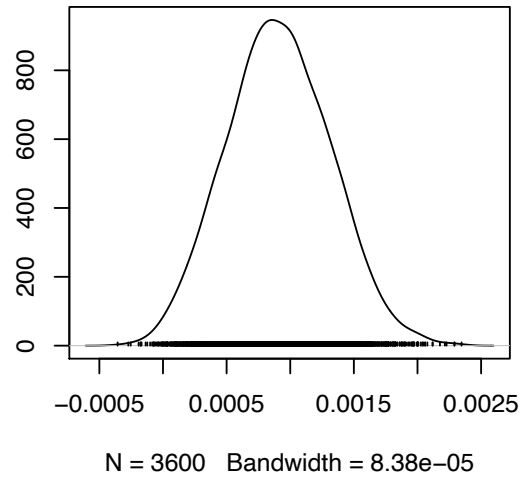
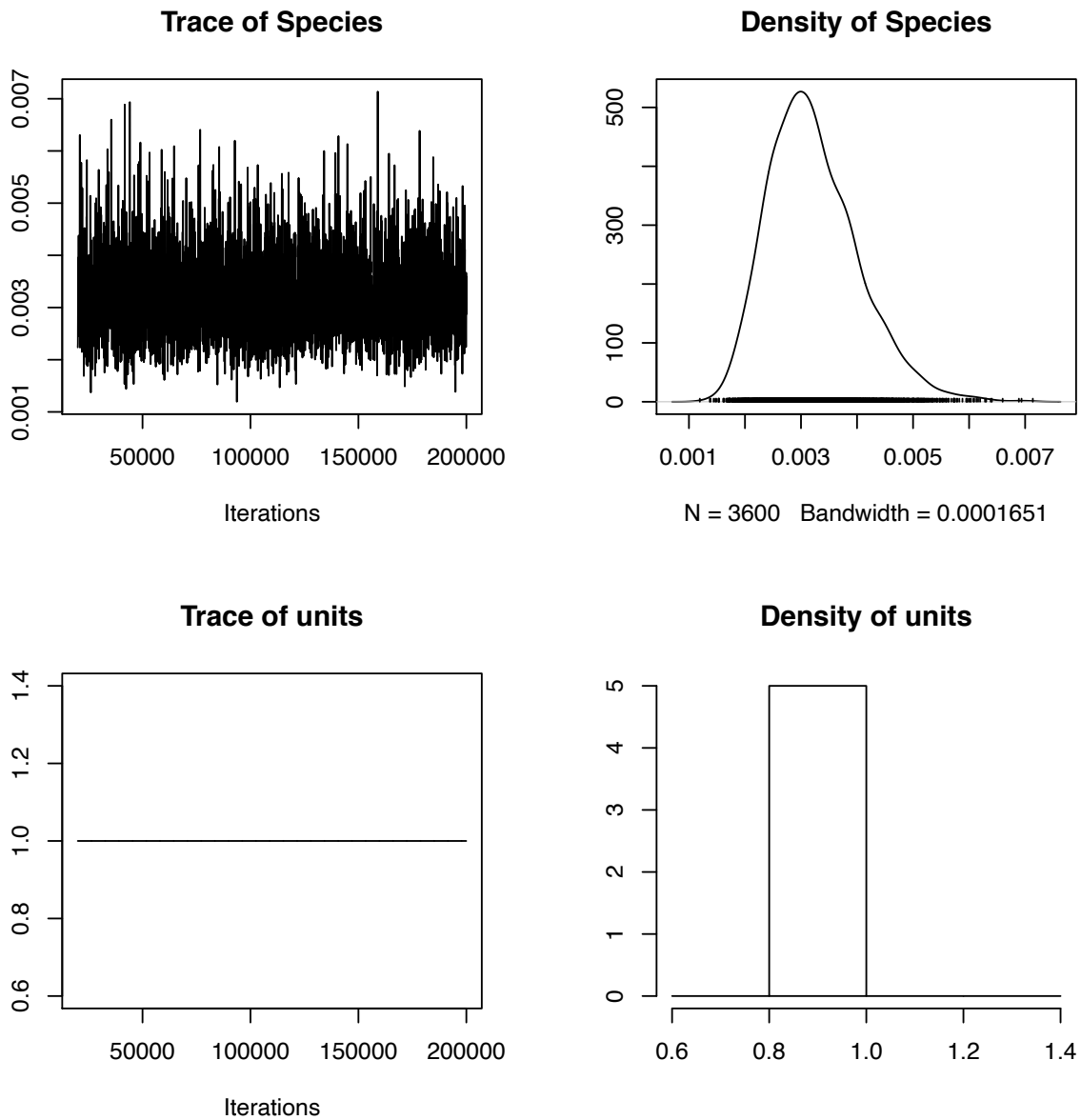


Figure S8, B



**Figure S8:** Panels A and B show the trace and density estimates of Model 6, a phylogenetic mixed effects model using species' range expansions to explain odonate persistence in the United States of America, with species as a random effect. 200 000 iterations were run to produce these results. These plots verify model convergence and absence of autocorrelation within the explanatory variables.

## Section S4: Supplementary Table S1

**Table S1:** Credible intervals of all MCMCglmm models considered to assess the effects of four global change variables, as well as species Northern range limit shifts, on odonate persistence across the United States of America. All models except Model 5 take phylogeny into account.

	Lower credible interval	Upper credible interval
<b>Model 1</b>		
(Intercept)	-0.1612	1.5876
Pesticides	-0.2935	-0.1356
Temperature	-0.1105	0.0508
Precipitation	0.0242	0.1337
Land use	-0.0274	0.0954
Sampling intensity	0.0410	0.1643
<b>Model 2</b>		
(Intercept)	-0.2042	1.6062
Pesticides	-0.3764	-0.2058
Temperature	-0.0024	0.1806
Precipitation	0.0054	0.1172
Land use	-0.1312	0.0083
Sampling intensity	-0.0590	0.0779
Pesticides:Temperature	-0.5475	-0.2617
<b>Model 3</b>		
(Intercept)	-0.0775	1.7808
Pesticides	-0.3738	-0.1666
Temperature	-0.1243	0.0422
Precipitation	-0.0185	0.1096
Land use	-0.0486	0.0830
Sampling intensity	0.0417	0.1661
Pesticides:Precipitation	-0.0594	0.0013
<b>Model 4</b>		
(Intercept)	-0.2004	1.6517
Pesticides	-0.3776	-0.1720
Temperature	-0.0019	0.1903
Precipitation	0.0056	0.1353
Land use	-0.1294	0.0123
Sampling intensity	-0.0688	0.0749
Pesticides:Temperature	-0.5787	-0.2687
Pesticides:Precipitation	-0.0200	0.0448
<b>Model 5</b>		
(Intercept)	0.6494	0.8962
Pesticides	-0.3660	-0.1985
Temperature	-0.0202	0.1708
Precipitation	-0.0060	0.1074
Land use	-0.1307	0.0080
Sampling intensity	-0.0552	0.0808
Pesticides:Temperature	-0.5428	-0.2615
<b>Model 6</b>		
(Intercept)	-0.3052	1.6396
Range expansion	0.0001	0.0016

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3. Abbott, J. C. OdonataCentral: An online resource for the distribution and identification of Odonata. <http://www.odonatacentral.org> (2020).
4. Ontario Odonata Atlas Database. Natural Heritage Information Centre, Ontario Ministry of Natural Resources and Forestry. Queried on Aug 30, 2018 by C.D. Jones. (2018).
5. Favret, C., De Serres, J. M., Larrivée, M. & Lessard, J. P. The Odonata of Quebec: Specimen data from seven collections. *Biodivers. Data J.* **8**, (2020).