

The coevolutionary mosaic of betacoronavirus emergence risk

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Driven by the need to understand the ecological factors involved in the emergence of *Betacoronavirus* (the genus causing the SARS, MERS, and COVID-19 in human) through bat hosts, we develop an approach to the assessment of spillover risk based on the Geographic Mosaic Theory of Coevolution. In doing so, we provide a global mapping of the spillover risk posed by betacoronaviruses, reflecting the fact that this risk is best understood through the multi-faceted prism of ecological and evolutionary mechanisms. Our framework reveals that host richness alone, although a component of viral hazard, is not a sufficiently integrative predictor of risk. We offer alternative insights based on viral sharing, host compositional uniqueness, and host phylogenetic diversity and phylogeographic regions. By comparing our aggregated measure of risk to a proxy for human density, namely the proportion of each pixel that is covered by urban or built land, we provide a synthetic risk map, allowing the identification of hotspots where the bat-betacoronavirus interaction network may facilitate the emergence of novel viruses and their spillover into human populations.

1 Disease emergence is complex, and is driven not only by animal-human contact, but also by the
2 underlying evolutionary dynamics in viral reservoirs.¹ Although host richness is often used as a superficial
3 proxy for spillover risk,^{2,3} these approaches oversimplify the relevant interspecific heterogeneity in
4 immunology, behavior, and other traits, and therefore overlook unique host pools that allow for the rapid
5 evolution of highly divergent viruses.⁴ In the case of generalist pathogens like betacoronaviruses, there is
6 conceptual and empirical support to the idea that these community-level mechanisms are even more
7 important,⁵ particularly given that cross-species transmission may, as a rule, structure viral evolution
8 more than co-divergence with hosts.⁶ This creates a disconnect between coevolutionary theory (including
9 empirical evidence from virology) and most existing ecological frameworks for mapping spillover risk.

10 The Geographic Mosaic Theory of Coevolution (GMTC) attempts to explicitly connect microevolutionary
11 dynamics to the macroecology and biogeography of symbiotic interactions.⁷ The GMTC posits that
12 coevolutionary processes among pairs⁸ or complexes⁹ of species are structured in space by the rippling
13 effects of abiotic conditions onto evolutionary mechanism, giving rise to fragmented systems with
14 different structure and ecologically dynamics over large spatial extents.¹⁰ The GMTC predicts a spatial
15 fragmentation of coevolutionary dynamics under the joint action of three processes:¹¹ coevolutionary hot-
16 and coldspots, which appear when the intensity of *interaction* (in terms of reciprocal fitness consequences)
17 varies spatially; selection mosaics, wherein the intensity of *selection* varies across space, driven by both the
18 biotic complexity of the community (locally diverse hosts and viruses are more biotically complex) and the
19 local favorability of the environment;¹² and trait remixing, which occurs when coevolutionary dynamics
20 are driven by the arrival (or departure) of *functional traits*, through changes in community composition
21 due to invasions, meta-community dynamics, and dispersal.

22 Here, we apply the GMTC to explore and explain the global biogeography of betacoronaviruses, the group
23 that includes SARS-CoV, MERS-CoV, and SARS-CoV-2. In their bat reservoirs, coronaviruses evolve
24 through a mix of host jumps, recombination among disparate lineages, and, to a lesser degree,
25 co-divergence with their hosts—²a mix of mechanisms that creates a complex and nonlinear relationship
26 between host diversity and viral emergence. Working from a recently published database of bat hosts of
27 betacoronaviruses, we test whether spatial structure in bat-betacoronavirus coevolution is identifiable at a
28 global scale. Aiming to explain these patterns, we develop a generalized framework for applying the
29 GMTC to host-virus interactions, with a specific emphasis on the potential to create independent
30 coevolutionary dynamics (and therefore spatial fragmentation in risk) through heterogeneity. We develop

31 a trivariate risk assessment system that connects each GMTC mechanism to a quantifiable aspect of
32 host-virus interactions: (i) viral sharing rates in host communities, representing the strength of potential
33 interaction between viruses and any one host (i.e., places where viruses undergo constant host switching
34 may be coevolutionary coldspots); (ii) the phylogenetic diversity of hosts, as a proxy for variation in the
35 immunological mechanisms that antagonize viruses (i.e., the selection mosaic); and (iii) the local
36 uniqueness of the bat community, representing the potential for viruses to be exposed to novel host traits
37 (e.g., variation in receptor sequences). Together, we argue that these can be used to identify and map the
38 evolutionary drivers that—in conjunction with transmission processes (e.g., viral prevalence in reservoirs
39 and animal-human contact rates)—determine disease emergence risk.

40 Results and Discussion

41 Hotspots of host richness and viral diversification are distinct

42 Bats, the second most diverse group of mammals, are found worldwide; gradients in their species
43 richness generally track broader patterns of mammal diversity, with a striking Neotropical hotspot
44 (especially in the Amazon basin) and a secondary hotspot centered in the southeast Asian peninsula.
45 These hotspots of bat diversity are generally presumed to be hotspots of viral adaptive radiation, and
46 therefore areas of concern for human health.^{2,13} However, the hotspots of bat betacoronavirus reservoirs
47 show a distinct pattern, with primary hotspots (both in terms of size and higher values) of host richness
48 situated primarily southeast Asia, parts of southern Europe, and to a lesser extent parts of Africa in the
49 -25-0 range of latitudes (fig. 1; top). Although hundreds of species likely host undiscovered
50 betacoronaviruses, machine learning predictions have suggested that these undiscovered reservoirs should
51 follow the same diversity gradient.¹⁴ In principle, these hotspots of locally-diverse, virus-rich bat
52 communities should drive more adaptive diversification in their viruses.

53 [Figure 1 about here.]

54 However, we find that the global pattern of betacoronavirus phylogenetic distinctiveness is quite distinct
55 from both bat host richness and phylogenetic distinctiveness (fig. 1; bottom). In contrast to the sparsity of
56 Neotropical betacoronavirus hosts, South America has the most evolutionary distinct hosts *and* viruses,

57 followed by secondary hotspots in southeast Asia and the Rift Valley region have mostly distinct viruses.
58 Some degree of sampling bias may contribute to these patterns: for example, South-America is one of the
59 places where the fewest bat betacoronavirus sequences have been generated,^{2,13,15} resulting in a sparser
60 phylogenetic tree, and artificially inflating distinctiveness; conversely, disproportionate research effort in
61 eastern China¹⁶ may have led to a more complete inventory of the local diversity of coronaviruses, again
62 inflating these metrics relative to underlying patterns. Even accounting for these potential biases, though,
63 there is obvious heterogeneity in betacoronavirus evolutionary distinctiveness that is distinct from overall
64 bat diversity.

65 On closer inspection, these patterns recapitulate the evolutionary history of both the order Chiroptera and
66 the genus *Betacoronavirus*. Horseshoe bats (Rhinolophidae) are both the reservoirs of the SARS-like
67 viruses (subgenus *Sarbecovirus*), the group of pandemic threats that have been of the greatest interest to
68 researchers¹⁷ (and so have been sampled most intensively).¹⁶ The hotspots of host richness and viral
69 diversity in southeast Asia—both of which are disproportionately high, considering the global landscape
70 of bat species richness—are almost entirely driven by viral adaptive radiation through host switching
71 within this clade^{3,14}. In contrast, the Neotropical hotspot of viral distinctiveness is driven by isolation by
72 host vicariance. Out of the four main groups of betacoronaviruses, only the subgenus *Merbecovirus*
73 (MERS-like viruses) has been found in animals in the Americas—an introduction that is generally
74 presumed to be ancient.³ While comparatively understudied, New World merbecoviruses have been found
75 in the ghost-faced bats (Mormoopidae), New World leaf-nosed bats (Phyllostomidae), and free-tailed bats
76 (Molossidae) (add cite: Olival 2020 PLoS Pathogens). The former two groups are endemic to the
77 Neotropics, while the explosive adaptive radiations of the latter two (and particularly the phyllostomids)
78 are responsible for the hotspot of bat diversity in the Amazon. Together, these clades of New World bats
79 play host to a distinct regime of betacoronavirus coevolution.

80 **Global biogeographic regions are consistent for bats and betacoronaviruses**

81 Most previous work has assumed that coronavirus biogeography is driven by coevolutionary regimes that
82 form at finer taxonomic scales, treating the presence or richness of key bat host groups as predictive of
83 these viruses' distribution.^{2,3} Projecting bat and betacoronavirus phylogeny over space (fig. 2), we find
84 further support for the idea that bat community assembly is directly responsible for spatial heterogeneity
85 in viral coevolutionary regimes. The distinct groupings (represented by different colors, symbolizing

86 positions in a subspace formed by the first two phylogenetic principal components) are essentially
87 equivalent between the two groups, and can be coarsely delineated as (1) south and southeast Asia, (2)
88 east Asia (including northern China), west Asia, and the Mediterranean coast; (3) Eurasia above a
89 northing of 40; and (4) Africa and south America. In some cases, this diverges from expectations about
90 coronavirus biogeography: for example, previous work has rarely flagged India as a region of concern, but
91 for both bats and betacoronaviruses, the subcontinent falls into the same phylogeographic regions as the
92 southeast Asian peninsula (and indeed, the region is home to known bat hosts of nobecoviruses,
93 sarbecoviruses, and merbecoviruses).³

94 [Figure 2 about here.]

95 Overall, these results suggest that, although there are unique hotspots of viral adaptive radiation,
96 biogeographic regions are mostly consistent between bats and their viruses. This may be surprising, given
97 that cospeciation plays a minor role in coronavirus diversification,² which could theoretically allow for
98 broad divergence in their biogeography. However, host jumps at the family level or higher are relatively
99 rare and significant events in coronavirus evolutionary history,^{2,17} as a result, we suggest the mosaic of
100 betacoronavirus phylogeny is assembled from a set of overlapping smaller coevolutionary systems,
101 superimposed in space and filtered by the importance of different subgroups in local host communities.
102 For example, the most speciose and cosmopolitan family of bats, the vesper bats (Vespertilionidae), are
103 considered the primary reservoir of merbecoviruses;^{3,17} but in the Americas, where merbecoviruses are
104 the only lineage present, they have only been found in other bat taxa. At the coarsest scale, these
105 heterogeneities are lost, and betacoronavirus biogeography tracks the deep rifts in bat evolutionary
106 history—but within these broad regions, the component coevolutionary systems can have very different
107 dynamics.

108 **Coevolution-informed emergence risk is different in space**

109 As host richness, joint distinctiveness, or phylogeographic structure suggest that the bat-betacoronaviruses
110 complex is globally fragmented enough to give rise to both different levels of risk (as evidenced by the
111 spatial location of spillover events) and different types of co-evolutionary dynamics, we turn to the
112 Geographic Mosaic Theory of Coevolution to provide a measure of risk accounting for multiple processes.
113 In fig. 3, we overlapped three components of spillover risk: viral sharing, *i.e.* the chance that two bats will

114 share viruses overall; Local Contribution to Beta Diversity, *i.e.* the fact that a bat community is
115 compositionally unique compared to the average compositional similarity across the entire system; finally,
116 host phylogenetic diversity, *i.e.* how dispersed the bats in a location are within the tree of life. This
117 approach leads to the definition of broad biogeographic regions of risk, where the same color represents
118 the same type of risk. By way of contrast to figures fig. 1 and fig. 2, these regions do not necessarily
119 overlap with previous spatial partitions of the bat-betacoronaviruses complex.

120 [Figure 3 about here.]

121 From the perspective of spillover risk, the most important combination of factors is a high phylogenetic
122 diversity of hosts with low viral sharing; this, essentially, means that very different betacoronaviruses
123 could co-exist within the same place. This is particularly the case given that betacoronaviruses often
124 evolve and even achieve host shifts through recombination, which requires the co-occurrence of
125 sufficiently distinct viruses to be a major driver of emergence. In fig. 3, this corresponds to yellow to pale
126 green areas, which are essentially limited to South-Eastern Asia, and to some part of Sub-Saharan Africa.
127 Adopting a geographic mosaic theory perspective on risk, other regions of the world are of lesser concern
128 (fig. 4). Our risk decomposition does not account for viral diversity or distinctiveness. The simple
129 rationale behind it is that the acquisition of viral data is rarely disconnected from the acquisition of host
130 data. There are more sources of information on hosts than on viruses, allowing to develop a host-centric
131 perspective on risk (although this estimate would be more accurate with viral traits related to *e.g.* ability to
132 switch hosts or pathogenic potential). Areas with high bat diversity and high turnover *may* facilitate the
133 evolutionary radiation of viruses, matching previous findings that the diversification of bat coronaviruses
134 is driven largely by host shifts (inter-genus or higher levels of cross-species transmission) and, to a lesser
135 degree, cospeciation and sharing, representing intra-genus cross-species transmission.² This
136 diversification is not an actual risk factor for spillover itself, but acts downstream of a spillover event by
137 increasing the random chance of the emergence of a virus with the raw genomic components required for
138 the potential to infect humans.

139 [Figure 4 about here.]

140 From another perspective, areas of high host uniqueness and virus sharing (red-to-pink) could provide
141 hotspots of *Betacoronavirus* risk through mixing of unique viruses (via codivergence) and in turn

142 recombination. Under our framework, such a hotspot was identified in Madagascar, where most bat
143 species are endemic following evolutionary divergence from sister species in both African and Asian
144 continents.¹⁸ Recent surveillance¹⁹ has identified a novel *Betacoronavirus* (in the subgenus *Nobecovirus*) in
145 Madagascar-endemic pteropid bat species (*Pteropus rufus*, *Rousettus madagascariensis*), emphasizing
146 strong proof of principle in model predictions.

147 Human occupancy drives different levels of effective risk globally

148 Based on the previous result, we extracted the risk component from the composite map (see Methods), to
149 provide a single measure of risk varying between 0 and 1. This measure is presented in fig. 4. As this map
150 represents the potential risk, it must be weighed by the potential for contacts with humans. As a proxy for
151 this measure, we used the proportion of build/urban land from the EarthEnv dataset: this is a reasonable
152 proxy for the density of humans per unit area, which increases the probability of pathogen spread more
153 widely.²⁰ Since human activity is required to amplify the frequency of virus encounters and thus create
154 areas of viral amplification, mapping the potential risk against measures of land use is required to generate
155 a more actionable assessment of risk. This map is presented in fig. 5. Most of South America and Europe
156 are at comparatively lower risk, as although densely populated, settlements tend to be in areas with lower
157 potential risk. Regions like Malaysia and the North coast of Australia have a high risk component, but
158 should represent a relatively lower effective risk due to low human density. However, this mapping reveals
159 that South-East Asia, the Indian subcontinent, and parts of sub-Saharan Africa, are at high risk due to the
160 overlap between built areas and bat communities representing more opportunities for cross-species
161 transmission of betacoronaviruses. In looking for the origins of SARS in China,²¹ present serological
162 evidence that strongest human-animal contact results in higher risk of virus exposure, regardless of the
163 animal species, but that different types of contact had different impacts. Ideally, finer-grained information
164 about human activity (rather than human presence through anthropisation) could allow to partition this
165 risk further, albeit at the cost of more hypotheses required to estimate the amount of risk represented by
166 each activity. Our map of purported high risk/diversitification potential (Madagascar, South-America)
167 overlay with sampling gaps for *Betacoronavirus*,¹⁶ stressing the need for spatially targeted monitoring and
168 discovery.

169

[Figure 5 about here.]

170 PUT THIS SOMEWHERE: Available information describing the spillover of zoonotic betacoronaviruses of
171 bat origin where data was available before and up through the COVID-19 pandemic puts spillover events
172 of SARS-CoV-2 in Wuhan, China; SARS-CoV in Guangdong, China based on the presence of closest
173 known viruses circulating in nature, and a nearby location where serological (antibody) evidence has
174 indicated human exposure to SARS-like viruses;²² MERS-CoV in Saudi Arabia based on index cases
175 available from a recently-published compendium of cases.²³ For the latest event, most if not all index cases
176 are presumed to be camel-to-human transmission, and the precise origin point (if it exists) of MERS-CoV
177 in bats is uncertain. Recent recombinant canine coronavirus spillover events in Haiti²⁴ and Europe²⁵ are
178 not relevant here, as bats' involvement in these cycles of transmission have been supposed to be
179 non-existent. These index cases fall within different phylogeographic bioregions (fig. 2), which further
180 highlight the issue that different host-virus sub-systems may lead to widespread emergence.

181 Conclusion

182 Bats are important reservoir hosts for different classes of microorganisms, many of which a threat to
183 human health.^{26,27} Chiropterans emerged around 64 million years ago and are one of the most diverse
184 mammalian orders, with an estimated richness of more than 1400 species.^{28,29} They exhibit a broad variety
185 of habitat use, behaviour, and feeding strategies, putting them at key positions in the delivery and
186 provisioning of several ecosystem services, tied to important ecosystem-derived benefits to human.³⁰ For
187 example, bats are an essential component of many seed-dispersal networks.³¹ Over two-thirds of bats are
188 know to be either obligate or facultative insectivores, therefore actively contributing for agricultural pest
189 control,^{32,33} and vectors of pathogens that put a risk on human health.^{34,35} Because bats are globally
190 distributed and have a long evolutionary history, phylogeographic and biogeographic approaches are
191 required to shed light on the contemporary distribution of coevolutionary processes between bats and the
192 pathogens they host. Not all areas in which bats, viruses, and human are co-occurring are facing a risk of
193 spillover towards human populations, and the areas in which this risk exist may not be facing risks of the
194 same nature and magnitude.

195 Here, we propose a simple framework with broad explanatory power that helps contextualize discoveries
196 like highly divergent nobecoviruses in Madagascar and the previously-neglected adaptive radiation of
197 sarbecoviruses outside of southern China and throughout southeast Asia. In doing so, it advances

198 ecological theory beyond the current state of the art for global maps of emergence risk. For example,
199 previous studies that have used host richness as proxy have predicted a high diversity of unsampled bat
200 viruses,¹³ bat coronaviruses,² and even specifically betacoronaviruses¹⁴ in both the Amazon and southeast
201 Asia. While we find that both regions are characterized by highly divergent host and viral communities,
202 our framework identifies key differences between the regions. We find that Latin America is a hotspot of
203 both host and viral distinctiveness, suggesting that this branch of the bat-betacoronavirus complex may be
204 undergoing independent evolutionary dynamics from the rest of the global pool, but with limited potential
205 for viral diversification—a finding that is supported by previous work indicating a higher rate of
206 codivergence in Latin America.² In contrast, in southeast Asia, host richness and viral distinctiveness are
207 high but sharing is low; this suggests a different type of evolutionary dynamics that could generate high
208 local diversity of viruses through host switching and viral recombination (see e.g.,¹⁷ as well as the
209 discovery of recombinant viruses that share genetic material from both the SARS-CoV and SARS-CoV-2
210 branches of the Sarbecovirus lineage).³⁶ Both of these regions are priority areas for sampling, especially
211 given predictions that they contain many bat hosts of undiscovered betacoronaviruses.^{14,16} However, both
212 the evolutionary and ecological aspects of emergence risk are likely higher in southeast Asia—a fact that
213 will only become more relevant, as bats track shifting climates and exchange viruses with other species,
214 creating a hotspot of cross-species transmission unique to the region.³⁷

215 The diversity and diversification potential of bats responds to anthropogenic factors others than shifting
216 climates.³⁸ Land use changes could significantly decrease bat suitability, notably through effects on diet
217 and availability of habitats.³⁹ As our results establish that the diversification of bats betacoronaviruses
218 happens on top of processes affecting hosts, biogeographic variation in human population density and
219 anthropogenic disturbances may feed into co-evolutionary dynamics. Increase in humans-hosts contacts
220 also increase the risk of emergence of novel diseases,⁴⁰ so does the changes in landscape connectivity at
221 local/regional scales.⁴¹ This represents a challenge for both conservation strategies and disease ecology:
222 some areas can a high emergence risk and more potential for the acquisition of zoonotic viruses through
223 bat-human encounters.⁴² In particular, the challenge ahead lies in the need to quantify actual exposure
224 (and risk) accounting for several transmission scenarios, including both direct and indirect bat - human
225 interactions, and feeding back into the provision of ecosystem services by bats.

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236 **Methods**

237 **Known *Betacoronavirus* hosts**

238 We downloaded the data on bats hosts of *Betacoronavirus* from
239 <https://www.viralemergence.org/betacov> on Apr. 2022,¹⁴ and filtered it to “known” hosts (established
240 before the emergence of SARS-CoV-2) and “novel” hosts (confirmed through sampling and competence
241 assays since the initial data collection). The original database was assembled by a combination of data
242 mining and literature surveys, including automated alerts on the “bats” and “coronavirus” keywords to
243 identify novel empirical evidence of bats-betacoronaviruses associations; this yielded a total of 126 known
244 hosts, 47 of which were novel hosts.

245 **Bat occurrences**

246 We downloaded the rangemap of every current bat species that was classified as an empirically
247 documented host of *Betacoronavirus* from the previous step, according to recent IUCN data.⁴³ The range
248 maps were subsequently rasterized using the rasterize function from GDAL⁴⁴ at a resolution of
249 approximately 100kmx100km. For every pixel in the resulting raster where at least one bat host of
250 *Betacoronavirus* was present, we extract the species pool (list of all known bat hosts), which was used to
251 calculate the following risk assessment components: bat phylogenetic diversity, bat compositional
252 uniqueness, and predicted viral sharing risk.

253 **Bat phylogenetic diversity**

254 For every pixel, we measured Faith’s Phylogenetic Diversity⁴⁵ based on a recent synthetic tree with robust
255 time calibration, covering about 6000 mammalian species.⁴⁶ Faith’s PD measures the sum of unique
256 branches from an arbitrary root to a set of tips, and comparatively larger values indicate a more
257 phylogenetic diverse species pool. We measured phylogenetic diversity starting from the root of the entire
258 tree (and not from Chiroptera); this bears no consequences on the resulting values, since all branches
259 leading up to Chiroptera are only counted one per species pool, and (as we explain when describing the
260 assembly of the composite risk map), all individual risk components are ranged in [0,1]. This measure
261 incorporates a richness component, which we chose not to correct for; the interpretation of the

262 phylogenetic diversity is therefore a weighted species richness, that accounts for phylogenetic
263 over/under-dispersal in some places.

264 **Bat compositional uniqueness**

265 For every species pool, we measured its Local Contribution to Beta-Diversity;⁴⁷ LCBD works from a
266 species-data matrix (traditionally noted as \mathbf{Y}), where species are rows and sites are columns, and a value of
267 1 indicates occurrence. We extracted the \mathbf{Y} matrix assuming that every pixel represents a unique location,
268 and following best practices⁴⁸ transformed it using Hellinger's distance to account for unequal bat
269 richness at different pixels. The correction of raw community data is particularly important for two
270 reasons: first, it prevents the artifact of richer sites having higher importance; second, it removes the effect
271 of overall species richness, which is already incorporated in the phylogenetic diversity component. High
272 values of LCBD indicate that the pixel has a community that is on average more dissimilar in species
273 composition than what is expected knowing the entire matrix, i.e. a more unique community. Recent
274 results by⁴⁹ shows that LCBD measures are robust with regards to spatial scale, and are therefore
275 applicable at the global scale.

276 **Viral sharing between hosts**

277 For all bat hosts of *Betacoronavirus*, we extracted their predicted viral sharing network, generated from a
278 previously published generalized additive mixed model of virus sharing by a tensor function of
279 phylogenetic distance and geographic range overlap across mammals.⁵⁰ This network stores pairwise
280 values of viral community similarity. To project viral sharing values into a single value for every pixel, we
281 averaged the pairwise scores. High values of the average sharing propensity means that this specific extant
282 bat assemblage is likely to be proficient at exchanging viruses.

283 **Composite risk map**

284 To visualize the aggregated risk at the global scale, we combine the three individual risk components
285 (phylogenetic diversity, compositional uniqueness, and viral sharing) using an additive color model.⁵¹ In
286 this approach, every risk component gets assigned a component in the RGB color model (phylogenetic
287 diversity is green, compositional uniqueness is red, and viral sharing is blue). In order to achieve a valid

288 RGB measure, all components are re-scaled to the [0,1] interval, so that a pixel with no sharing, no
289 phylogenetic diversity, and no compositional uniqueness is black, and a pixel with maximal values for
290 each is white. This additive model conveys both the intensity of the overall risk, but also the nature of the
291 risk as colors diverge towards combinations of values for three risk components. Out of the possible
292 combinations, the most risky in terms of rapid diversification and spillover potential is high phylogenetic
293 diversity and low viral sharing,⁵² in that this allows multiple independent host-virus coevolutionary
294 dynamics to take place in the same location. In the colorimetric space, this corresponds to yellow – because
295 the HSV space is more amenable to calculations for feature extraction,⁵³ we measured the risk level by
296 calculating the angular distance of the hue of each pixel to a reference value of 60 (yellow), and weighted
297 this risk level by the value component. Specifically, given a pixel with colorimetric coordinates (h, s, v) , its
298 ranged weighted risk value is

$$v \times \left[1 - \frac{|\text{atan}(\cos(\text{rad}(h)), \sin(\text{rad}(h))) - X|}{2\pi} \right],$$

299 where X is $\text{atan}(\cos(\text{rad}(60)), \sin(\text{rad}(60)))$, a constant approximately equal to 0.5235.

300 **Viral phyogeography and evolutionary diversification**

301 To next represent phyogeography of betacoronaviruses in bats, we aggregated and analyzed
302 betacoronavirus sequence data. We used the following query to pull all *Betacoronavirus* sequence data
303 from the GenBank Nucleotide database except SARS-CoV-2; (“Betacoronavirus”[Organism] OR
304 betacoronavirus[All Fields]) NOT (“Severe acute respiratory syndrome coronavirus 2”[Organism] OR
305 sars-cov-2[All Fields]). We added a single representative sequence for SARS-CoV-2 and manually curated
306 to remove sequences without the RNA-dependent RNA polymerase (RdRp) sequence or that contained
307 words indicating recombinant or laboratory strains including “patent”, “mutant”, “GFP”, and
308 “recombinant”. We filtered over-represented taxa including betacoronavirus 1, hCoV-OC43, Middle East
309 respiratory syndrome coronavirus, Murine hepatitis virus, and hCoV-HKU1. Curated betacoronavirus
310 RdRp sequences were then aligned using MAFFT⁵⁴ v1.4.0 (Algorithm FFT-NS-2, Scoring matrix 200PAM /
311 k=2, gap open penalty 1.53m offset value 0.123) and a maximum likelihood tree reconstructed in
312 IQ-TREE⁵⁵ v1.6.12 with ModelFinder⁵⁶ ultrafast bootstrap approximation⁵⁷ with a general time reversible
313 model with empirical base frequencies and the 5-discrete-rate-category FreeRaye model of nucleotide

314 substitution (GTR+F+R5).

315 We first tested the hypothesis that hotspots of viral diversification would track hotspots of bat
316 diversification. To do so, we plotted the number of known bat hosts (specifically only those included in the
317 phylogeny, so there was a 1:1 correspondence between data sources) against the “mean evolutionary
318 distinctiveness” of the associated viruses. To calculate this, we derived the fair proportions evolutionary
319 distinctiveness⁵⁸ for each of the viruses in the tree, then averaged these at the bat species level, projected
320 these values onto their geographic distributions, and averaged across every bat found in a given pixel. As
321 such, this can be thought of as a map of the mean evolutionary distinctiveness of the known viral
322 community believed to be associated with a particular subset of bats present.

323 **Co-distribution of hosts and viral hotspots**

324 Subsequently, we tested the hypothesis that the biogeography of bat betacoronaviruses should track the
325 biogeography of their hosts. To test this idea, we loosely adapted a method from,^{59,60} who proposed a
326 phylogenetic method for the delineation of animal biogeographic regions. In their original method, a
327 distance matrix - where each row or column represents a geographic raster’s grid cell, and the dissimilarity
328 values are the “beta diversity similarity” of their community assemble - undergoes non-metric
329 multidimensional scaling (NMDS); the first two axes of the NMDS are projected geographically using a
330 four-color bivariate map. Here, we build on this idea with an entirely novel methodology. First, we
331 measure the phylogenetic distance between the different viruses in the betacoronaviruses tree by using the
332 cophenetic function in ape;⁶¹ subsequently, we take a principal components analysis of that distance
333 matrix (readily interchangeable for NMDS in this case) to project the viral tree into an n-dimensional
334 space. We then take the first two principal components and, as with the evolutionary distinctiveness
335 analysis, aggregated these to a mean host value and projected them using a four-color bivariate map.

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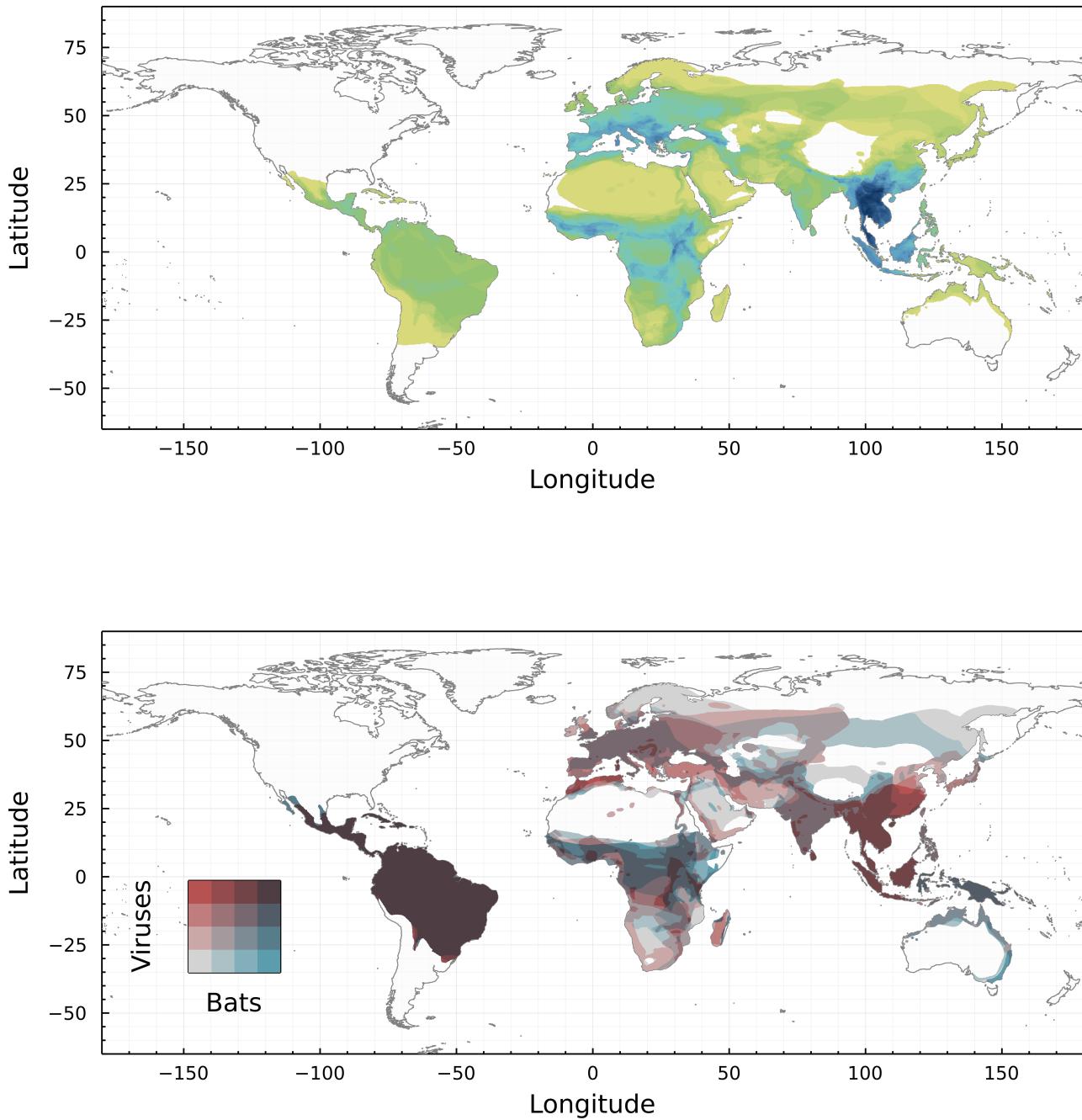


Figure 1: Top panel: relative diversity of known bat hosts of betacoronaviruses. This map shows that the region with the largest number of possible hosts is South-Eastern Asia. Bottom panel: congruence between the evolutionary distinctiveness of the hosts (grey to blue) and the viruses (grey to red).



Figure 2: Phylogeographic regions of bats (top) and viruses (bottom) based on the joint analysis of their occurrence and phylogenetic relatedness. The different colors show tendencies to separate alongside the first two components of a PCoA. Note that the PCoA for the bats and viruses are independent, and so cannot be compared directly – that being said, the regions can be compared across maps.

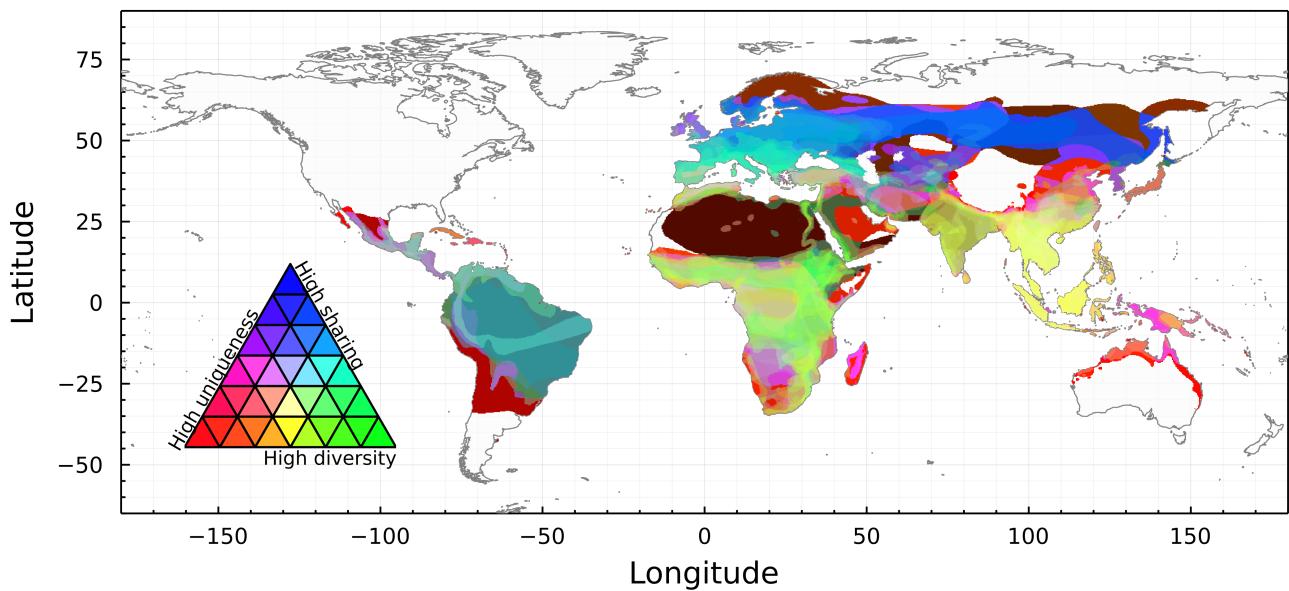


Figure 3: Trivariate additive mapping of the components of risk in the red/green/blue, where high virus sharing is encoded in the blue channel, host phylogenetic diversity in the green channel, and compositional uniqueness in the red channel. A pixel that would maximize all measures (highest possible risk) would be a pure white (specifically $\text{RGB}(1.0, 1.0, 1.0)$), and a pixel with the lowest possible values would be pure black (specifically $\text{RGB}(0.0, 0.0, 0.0)$). Therefore, lighter values (the sum of the three channels gets closer to 3) indicate higher risk, and the color indicates the proportional distribution of the factors making up the total risk.

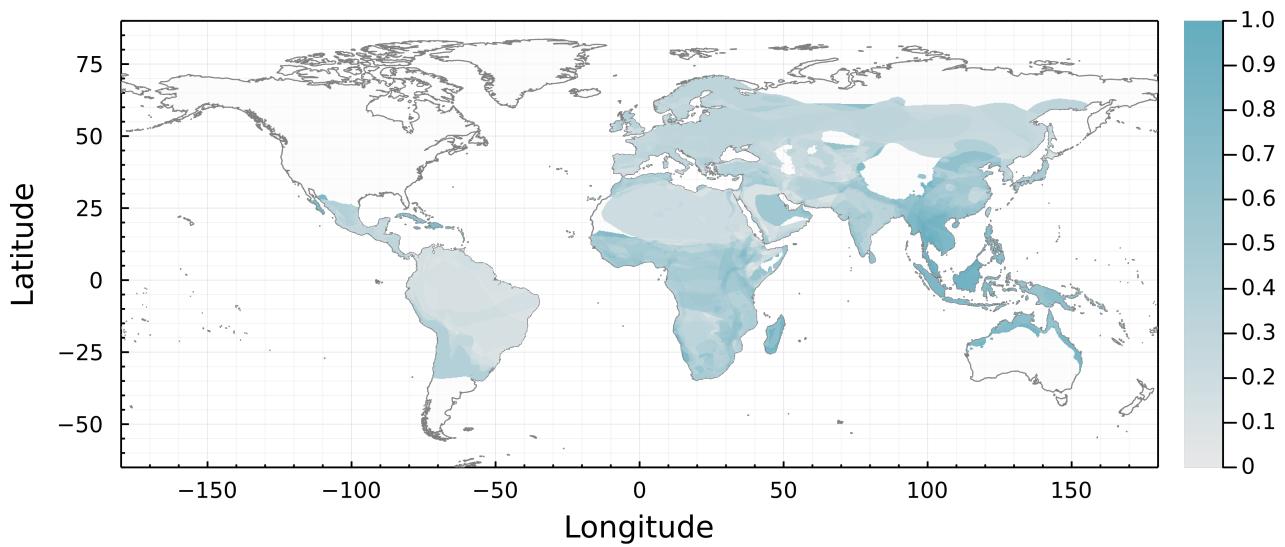


Figure 4: Extraction of a measure of *Betacoronavirus* spillover risk from bat hosts based on the colorimetric space from fig. 3. The risk is a composite measure of the color value and angular distance to the yellow hue, as defined in the methods, ranged in the unit space. Based on this analyses, regions at high risk of spillover are southeast Asia and Madagascar.

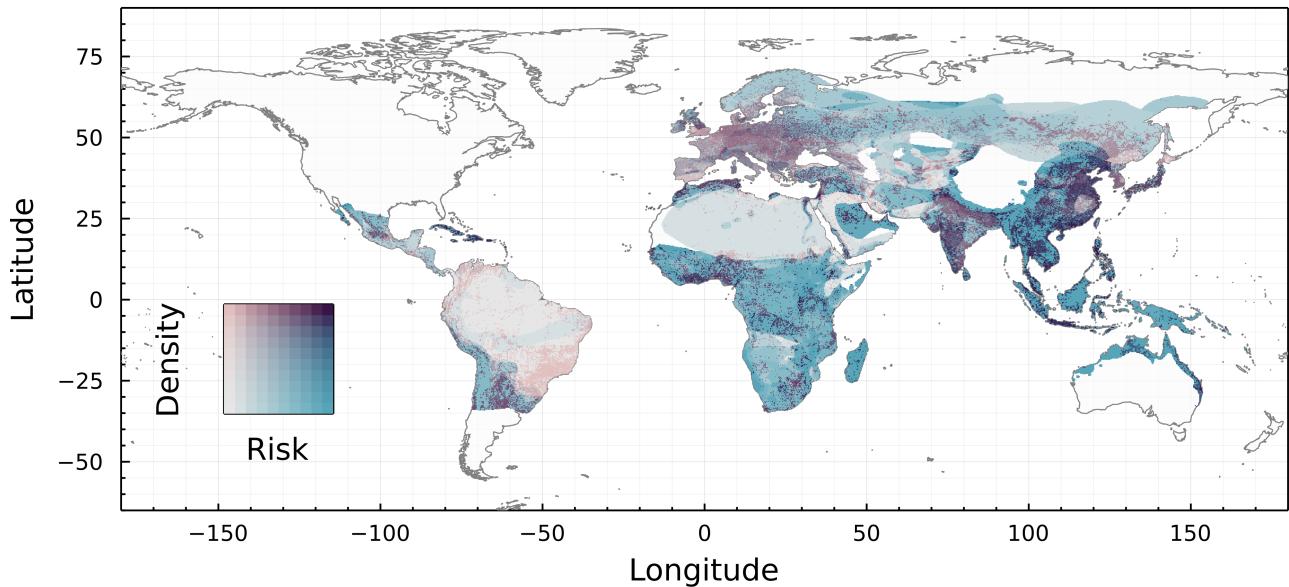


Figure 5: Overlap of the percent of each pixel occupied by urbanized structures, representing the degree of settlement, on the spillover risk map (where the risk comes only from wildlife, and ignores multi-hosts chains of transmissions including non-bats hosts). Darker pixels correspond to more risk, in that the GMTC-derived risk of fig. 4 is high *and* the pixel is densely occupied by human populations. This approach increases the relative risk of several regions in Africa, and highlights the risk in India, southeast China, and the Arabian peninsula where areas of high to moderate risk overlap with areas of denser population.