

1 **Benefits And Limitations Of Three-Dimensional Printing Technology For Ecological**  
2 **Research**

3

4 Jocelyn E. Behm<sup>1,2\*</sup>, Brenna R. Waite<sup>1</sup>, S. Tonia Hsieh<sup>3</sup>, and Matthew R. Helmus<sup>1</sup>

5

6 <sup>1</sup>Integrative Ecology Lab, Center for Biodiversity, Department of Biology, Temple University,  
7 Philadelphia, PA, USA

8 <sup>2</sup>Department of Ecological Science – Animal Ecology, VU University Amsterdam, Amsterdam,  
9 the Netherlands

10 <sup>3</sup>Department of Biology, Temple University, Philadelphia, PA, USA

11 **\*Correspondence:**

12 Jocelyn E. Behm

13 [jebehm@temple.edu](mailto:jebehm@temple.edu)

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29 **Abstract**

30 **Background:** Ecological research often involves sampling and manipulating non-model  
31 organisms that reside in heterogeneous environments. As such, ecologists often adapt techniques  
32 and ideas from industry and other scientific fields to design and build equipment, tools, and  
33 experimental contraptions custom-made for the ecological systems under study. Three-  
34 dimensional (3D) printing provides a way to rapidly produce identical and novel objects that  
35 could be used in ecological studies, yet ecologists have been slow to adopt this new technology.  
36 Here, we provide ecologists with an introduction to 3D printing.

37 **Results:** First, we give an overview of the ecological research areas in which 3D printing is  
38 predicted to be the most impactful and review current studies that have already used 3D printed  
39 objects. We then outline a methodological workflow for integrating 3D printing into an  
40 ecological research program and give a detailed example of a successful implementation of our  
41 3D printing workflow for 3D printed models of the brown anole, *Anolis sagrei*, for a field  
42 predation study. After testing two print media in the field, we show that the models printed from  
43 the less expensive and more sustainable material (blend of 70% plastic and 30% recycled wood  
44 fiber) were just as durable and had equal predator attack rates as the more expensive material  
45 (100% virgin plastic).

46 **Conclusions:** Overall, 3D printing can provide time and cost savings to ecologists, and with  
47 recent advances in less toxic, biodegradable, and recyclable print materials, ecologists can  
48 choose to minimize social and environmental impacts associated with 3D printing. The main  
49 hurdles for implementing 3D printing – availability of resources like printers, scanners, and  
50 software, as well as reaching proficiency in using 3D image software – may be easier to  
51 overcome at institutions with digital imaging centers run by knowledgeable staff. As with any

52 new technology, the benefits of 3D printing are specific to a particular project, and ecologists  
53 must consider the investments of developing usable 3D materials for research versus other  
54 methods of generating those materials.

55  
56 **Key Words:** 3D models, additive manufacturing, *Anolis sagrei*, clay model, Curaçao, Maya  
57 Autodesk, sustainability

## 58 **Background**

59 Ecologists exhibit exceptional creativity and ingenuity in designing new tools and  
60 equipment for their studies, often incorporating and repurposing technology from other fields.  
61 For example, unique solutions have been devised for tracking animals (backpack-mounted radio  
62 transmitters [1]), tracking seeds (fluorescent pigments [2]; seed tags [3]), catching animals (pit-  
63 less pitfall traps [4]), containing or restraining difficult-to-hold specimens (squeeze box for  
64 venomous snakes [5], ovagram for amphibian eggs [6]), and remotely collecting data or samples  
65 (frog logger [7]; hair trap [8]), among countless others. Because many ecological studies require  
66 customized equipment, ecologists are no strangers to building the contraptions necessary for  
67 conducting their research, and the weeks leading up to and during field seasons and lab  
68 experiments often involve multiple trips to hardware stores and craft shops.

69 Despite the high level of creativity and adaptability exhibited by ecologists, there is one  
70 technology that ecologists have been slower to adopt relative to other fields: three-dimensional  
71 (3D) printing. Additive layer manufacturing, or 3D printing, is the layering of material by a  
72 computer-controlled machine tool to create an object from a digital file that defines its geometry  
73 [9]. Most objects are printed in plastic, but newer print materials such as metal, wood, or other  
74 composites are increasingly common in consumer applications. In the recent past (i.e., before  
75 2010), 3D printing was cost-prohibitive and limited in availability, but it is now affordable and

76 accessible to budget-conscious ecologists. Many research institutions have at least one 3D  
77 printing center and 3D printing services are available to all online. Other fields, such as the  
78 health sciences, have readily adopted 3D printing into their research [e.g., 10], but it is as of yet  
79 an untapped technology that ecologists can exploit to their advantage.

80         Recent studies have highlighted the benefits of 3D printing in terms of cost and time  
81 efficiency [11,12], yet ecologists wanting to implement 3D printing for the first time must still  
82 traverse a steep learning curve. Our goal here is to flatten the curve and provide ecologists with a  
83 general but sufficient background in 3D printing technology to know what considerations are  
84 important when approaching a 3D printing project. In this article, we provide an overview of  
85 how 3D printing has been adopted by fields related to ecology. We highlight areas of ecological  
86 research where we believe 3D printing has the promise to be most effective, and provide a  
87 methodological workflow for integrating 3D printing into ecological studies. We illustrate this  
88 workflow using an example from our own work, which includes the obstacles we encountered  
89 and the solutions we devised. Finally, we conclude with important environmental sustainability  
90 considerations.

#### 91 *Overview of 3D printing in fields related to ecology*

92         Two disciplines that were early adopters of 3D printing technology and have strong  
93 connections to ecology are biomechanics and natural history curation. Below we provide  
94 examples of 3D printing implementations in these fields to provide ecologists with ideas of what  
95 is possible.

96         The aim of biomechanics is to understand the movement and structure of living  
97 organisms integrating across physics, engineering, physiology, and ecology. In biomechanics,  
98 3D printing is used to test how the shapes of particular appendages or biological structures

99 function in the physical environment without having to use live organisms. For example, 3D  
100 printed models of the sand-burrowing sandfish lizard's (*Scincus scincus*) respiratory system  
101 made it possible to study why it does not inhale sand in ways that are impossible with an actual  
102 respiratory system [13]. In studies of fluid dynamics, 3D printed models of swift (*Apus apus*)  
103 wings and bodies of echolocating bat species permitted tests in water and wind tunnels  
104 respectively to understand how morphology influences species' movements [14,15]. In other  
105 applications, biomechanical theory is tested by attaching 3D printed structures to robots. In a  
106 study of underwater burrowing mimetics in bivalves, Germann *et al.* [16] used mathematical  
107 models to design a bivalve shell which was 3D printed and incorporated into a burrowing robot.  
108 In other studies, evolutionary optimization models are used to design the shape of anatomical  
109 structures. Then, 3D prints of the modeled and naturally occurring structures are compared in  
110 performance tests to understand the evolutionary limitations species face in structural adaptation  
111 [17,18]. For these studies, 3D models enabled scientific inquiry, as manipulating live animals  
112 would have been challenging to impossible.

113         In the field of natural history curation, 3D printing increases the speed at which  
114 discoveries are made, and the rate at which data and resources are shared across natural history  
115 collections [19]. In paleontology, the reconstruction of complete skeletons is often impaired by  
116 the recovery of incomplete remains at dig sites. Mitsopoulou *et al.* [20] used mathematical  
117 allometric scaling models to calculate the dimensions of bones missing from the remains of a  
118 dwarf elephant (*Paleoloxodon tiliensis*) recovered from Charkadio Cave on Tilos Island, Greece.  
119 From these analyses, a 3D model was printed to allow the complete skeleton to be assembled. In  
120 addition, 3D technology also facilitates the sharing of museum material without having to loan  
121 valuable specimens, making it possible to construct complete skeletons using partial skeletons

122 from multiple separate collections [21]. In fact, museums have been quick to adopt 3D  
123 technology because it vastly improves the rate at which collections are shared. The exchange of  
124 3D-printed specimens facilitates crowd sourcing for specimen identification; access to high-  
125 quality replicas of endangered, extinct, or otherwise valuable and/or fragile specimens; and  
126 printed specimens can even be used in a field setting for species identification [21,22]. Museums  
127 are increasingly accepting deposits of 3D printed material for rare and/or difficult to access  
128 specimens. Lak *et al.* [23] employed 3D technology to describe two new damselfly species that  
129 were preserved in amber. Because it is difficult to physically extract amber-encased specimens  
130 without damaging them, the team used phase contrast X-ray synchrotron microradiography to  
131 make 3D images of the specimens, and deposited the 3D prints in several museums. Finally, 3D  
132 technology also accelerates the flow of information for education and outreach. For example,  
133 Bokor *et al.* [24], developed a classroom exercise where students print fossilized horse teeth and  
134 examine how the teeth changed over time with respect to changing climate.

### 135 *Integration of 3D printing in Ecology*

136 While ecologists have used 3D printing in a variety of applications (Table 1), there are  
137 four areas where we view 3D printing to be the most impactful: behavioral ecology, thermal  
138 ecology, building customized equipment, and enhancing collaboration.

139 The main goal of behavioral ecology is to understand how ecological and evolutionary  
140 forces shape behavior. In addition to observational studies, behavioral ecology research can  
141 involve manipulations of environmental conditions to test hypotheses. For testing hypotheses in  
142 both lab and field conditions, 3D printing may be incredibly useful for making precise,  
143 repeatable models. Three-dimensional printing has already been used to create precise models of  
144 bird eggs to test egg rejection behavior in the context of brood parasitism [25], zebrafish shoals

145 to test the effect of body size on zebrafish shoaling preferences [26], and artificial flower corollas  
146 to test the effect of floral traits on pollinator visitation [27–29] (Table 1). In these studies, 3D  
147 printing was chosen for its ability to create identical experimental stimuli because alternative  
148 methods, such as constructing models by hand, could introduce unintentional variation that  
149 makes it difficult to determine whether study subjects are responding to intentional or  
150 unintentional variation in experimental stimuli. In addition, 3D printing is often a faster method  
151 for creating models than making them by alternative methods [12]. There may be scenarios  
152 where 3D printing will not produce more biologically accurate models than other methods, but in  
153 many cases, 3D printing will increase the types of behavioral questions that can be asked [25].  
154 Within the field of behavioral ecology research, 3D printing can be used to test myriad behaviors  
155 including predation (see Results), reproduction, foraging, social interactions, and defense in both  
156 aquatic and terrestrial habitats.

157         Thermal ecology is focused on understanding how organisms are influenced by the  
158 temperature profile of their environment. A major challenge of thermal ecology research is  
159 constructing models that accurately replicate the thermal properties of a study organism. Copper  
160 models are often used, however, recent work demonstrated that 3D printed plastic models were  
161 cheaper and faster to construct and exhibited no difference in thermal properties compared to  
162 standard copper models (Table 1) [12]. This, as well as the need for high numbers of identical  
163 models, suggests that 3D printed models may make thermal ecology research more accessible.

164         Perhaps 3D printing will be the most helpful to the widest number of ecologists because  
165 it provides a method for constructing customized equipment such as tools and experimental  
166 habitats or mesocosms. In the field of soil ecology, 3D printing has been used to print artificial  
167 soil structures which accurately replicate the macropore structure of soil (Table 1) [30,31]. These

168 artificial soils are ideal replicate experimental mesocosms for soil macro- and/or  
169 microorganisms. Structures designed for other studies could be repurposed by ecologists as  
170 experimental habitats such as artificial gravel beds originally designed for testing water flow  
171 patterns [32] and artificial oyster shell reefs used to test how habitat complexity influences  
172 predation rates [33].

173       Opportunities for printing tools are limited primarily by the ecologists' imagination and  
174 range from simple structures to complex moving machines [34]. On the low-complexity end of  
175 the spectrum, 3D printing has been used to sample two difficult-to-catch, invasive, tree-boring  
176 beetle species that cause significant damage. Three-dimensional printed emergence traps make it  
177 possible to effectively trap and census invasive ambrosia beetles (*Euwallacea fornicates*) as they  
178 emerge from trees [35], while 3D printed decoys placed on standard beetle traps enhanced  
179 capture rates of invasive emerald ash borer beetles (*Agilus planipennis*) [11]. In a more complex  
180 application, whale researchers used 3D printing to build an unmanned surface vehicle named  
181 *SnotBot* which allows scientists to get close enough to whales to collect biological samples  
182 (Table 1) [36]. There are ample opportunities for ecologists to design tools to aid in data  
183 collection, sample processing, organism containment, and even organization of field or lab  
184 spaces.

185       From the examples provided above, designing custom materials certainly benefits  
186 scientists within the context of a particular study. However, the use of 3D technology also  
187 provides a mechanism for collaboration that extends beyond the limits of a single study.  
188 Ecological studies that are replicated across systems, geographic boundaries, latitudinal  
189 gradients, etc., are a powerful method for testing ecological theory [37]. The use of 3D  
190 technology facilitates these broad-scale studies through the sharing of identical tools, models,

191 and/or equipment that can be used in multiple systems. For example, 3D printed models of  
192 brown-headed cowbird (*Molothrus ater*) eggs [25] and Texas horned lizards (*Phrynosoma*  
193 *cornutum*) [12] can be used to test patterns of brood parasitism and thermal tolerances,  
194 respectively, across their geographic ranges. Similarly, for widespread invasive species like the  
195 emerald ash borer, sharing effective trap methodology [11] among scientists and agencies can  
196 potentially accelerate the rate at which the impact of the species is mitigated. In addition, 3D  
197 technology provides a useful platform for ecologists who would like to incorporate citizen  
198 scientists into a research program. Indeed, effective sampling technologies that can be  
199 disseminated electronically are ideal for citizen science, and increase the speed at which  
200 consistent data can be collected [38].

## 201 **Methods**

202 Below we describe a general workflow to use when embarking on incorporating 3D  
203 printing into ecological research. Essentially, once an ecologist has identified the object to be  
204 printed, the 3D printing process involves creating a printable 3D digital image file of the object,  
205 selecting an appropriate print media, and then printing draft and final versions of the object  
206 (Figure 1). To be clear, details specific to each project and available resources will need to be  
207 explored and fine-tuned along the way. However, our workflow highlights the major steps and  
208 aspects to consider at the onset.

### 209 *Make a digital object file*

210 The first step is to generate a digital file of the object to be printed, which can be  
211 accomplished by creating a digital file of the image from scratch, converting a 2D image (e.g.,  
212 photograph) into a 3D image, scanning an existing 3D object, or using an existing 3D file. All  
213 digital 3D files require use of software specifically for editing 3D images (Additional File 1).

214 The most common 3D image file format is an STL file and is used by many software packages.  
215 Depending on the image generating methods used and the types of modifications needed, there  
216 may be a significant learning curve to attain the necessary level of proficiency on the software.  
217 This is especially true for creating a 3D image completely from scratch (see below). In our  
218 experience, however, we scanned an existing object and an undergraduate student was able to  
219 work together with the printing center staff to learn the software and manipulate the image  
220 within two months.

221 Before trying to create the image from scratch or scan an existing image, it may be  
222 worthwhile first to check the many libraries of 3D imagery that are available online (Additional  
223 File 2). It is possible that a digital 3D file of a similar object has already been created and can be  
224 downloaded potentially for free, ready to be printed. Even if the file in an online library is not  
225 exactly perfect, it can be manipulated using 3D software (Additional File 1), which, depending  
226 on the modifications needed, may be a more efficient use of time than scanning an image or  
227 trying to draft an image from scratch.

228 If a suitable digital 3D file is not available, but the object to be printed is in the  
229 ecologist's possession, it is possible to use a 3D scanner to make a digital 3D image of the  
230 object, similar to how a flatbed scanner makes a digital 2D image of an object. There are various  
231 types of scanners, and it is necessary to choose a scanner that can accurately capture the level of  
232 detail from the object being scanned needed for the project. Laser scanners, structured light  
233 scanners, and even smart phone apps, can be used to create lower resolution scans of an object's  
234 external features. Laser scanners were used to scan Texas horned lizards that were frozen in  
235 realistic positions for a thermal ecology study (Makerbot Digitizer 3D, Makerbot, New York,  
236 USA) [12], and oyster shells for a biomechanical predation study (Vivid 9i, Konika Minolta Inc.,

237 Tokyo, Japan) [33]. For more complex and fine scale objects with both internal and external  
238 features like soil micropore structure, a method like X-ray microtomography is more appropriate  
239 (HMX 225, Nikon Corp., Tokyo, Japan) [30].

240         If the object to be printed is not in the ecologist's possession, it is possible to design the  
241 object using 3D drafting software (Additional File 1), with the time investment being  
242 proportional to the researcher's proficiency on the software and the complexity of the object.  
243 Using photogrammetry, photos can be digitized and 2D x,y coordinates from the photo converted  
244 into a 3D image [25,39]. Photogrammetry may be the easiest and most cost effective method,  
245 especially if a scanner is not available. Alternatively, mathematical formulae may be used to  
246 generate different shapes, such as the surface of a bird egg [25] or the curvature of a flower  
247 corolla [28]. Finally, it is possible to draft the object completely from scratch [e.g., 35], although  
248 a higher proficiency on the appropriate drafting software is necessary (Additional File 2).

249         Once a digital 3D image file is in hand, it will likely need to be edited and customized for  
250 the particular study. For example, in the brood parasitism study, the 3D image of the bird egg  
251 was edited to make it hollow so that the printed versions could be filled with water so their  
252 weight and thermal properties more closely matched a real bird egg [25]. Similarly, in the  
253 thermal ecology study, the 3D image of the Texas horned lizard was edited to include a well in  
254 the underside that fit a small environmental sensor (iButton) for measuring temperature [12].  
255 Object size can also be manipulated and various polygons added to include additional structures.

256         Depending on the type of printer and material used, the image may need to be edited to  
257 make printing possible and to efficiently use printing material. Non-manifold geometry errors  
258 (i.e., geometry that cannot exist in the real world) can be common in scans made on biological  
259 objects and must be corrected in order avoid fatal printing errors. Most 3D file manipulation

260 software allows for these corrections (Additional File 1). Because most printers print the object  
261 from the bottom up layer-by-layer, any appendages or protrusions that extend out much wider  
262 than the bottom layer may need added scaffolding to make the print possible. This scaffolding is  
263 removed after printing is completed with varying degrees of effort depending on the design and  
264 print material. In addition, if the object is not flat, it will likely need a flat base added to make it  
265 printable. If multiple copies of the object are to be printed, it may be possible to rotate or stack  
266 them so that several copies can be printed simultaneously. This method ensures efficient use of  
267 printing platform space and materials.

#### 268 *Printer and printing material*

269 There is a wide range of 3D printers that use various printing technologies and materials,  
270 and a comprehensive review of all printer types is beyond the scope of this article. Here, we  
271 focus on the printers and materials likely to be most useful to ecologists. Many factors must be  
272 weighed when choosing a printer and printing material for a project, such as cost, material  
273 durability, printed surface quality, timeframe for printing, and color. The most ubiquitous  
274 printers that are common on university campuses and also through commercial online printing  
275 services typically use either plastic-based filament or resin as the print material. Filament is hard  
276 plastic stored on spools that is melted and deposited as beads or streams during printing that  
277 quickly re-harden into layers to form the object. Resin is a polymer liquid that is layered and  
278 solidified with UV light. Both come in a range of colors; filament is often cheaper but leads to a  
279 lower resolution print with printed bands more prominent on the finished object, however if  
280 needed there may be applicable surface finishing methods for smoothing out these bands, like  
281 using acetone vapor. Filament may also be less durable for some applications and cracks can  
282 form between layers if the object is subjected to physical stress. Finished resin products are

283 generally smoother, can be printed at higher resolution, are more durable, and have the surface  
284 quality of a store-bought plastic item.

285 Both filament and resin have been used for printing low and high resolution ecological  
286 models, respectively. For example, acrylonitrile butadiene styrene (ABS), a type of filament, was  
287 used for printing artificial flowers [28], artificial zebrafish [26,40], and models of lizards [12],  
288 while resin was used for printing artificial soils with fine-scale pore structure in a hydrology  
289 study [31]. It is also worth considering the type of scaffolding involved with a specific printer/  
290 print material combination. For some printing set-ups, the scaffolding is the same material as the  
291 printed object, which means the scaffolding must be physically cut off, creating opportunities to  
292 damage the printed object. Other printers are capable of dual or multi-extrusion, meaning they  
293 can print using different materials simultaneously. In this case, the scaffold material differs from  
294 the print material and can be dissolved after printing in a chemical solvent solution.

295 More high-tech printers capable of printing even finer-scale and more-detailed objects  
296 use a powder based print material which is converted into a solid plastic with a laser. An  
297 advantage of this print material is that little scaffolding is needed and extra powder can quickly  
298 be removed by shaking or brushing. This media was used to print soil pore microstructure at the  
299 scale of micrometers [30]. These artificial soils were printed using Nylon 12, a material that can  
300 be autoclaved, which makes it possible to reuse the soils for multiple experiments [30]. Although  
301 most standard printing materials are various types of plastic, there are a handful of products that  
302 include other materials like wood, rubber, and metal. At least one biodegradable plastic filament  
303 also exists: a polylactic acid (PLA) made from corn starch [34,41]. Perhaps the most high-tech  
304 printers that have been used for an ecological application printed gelatin-based designer bacterial

305 ecosystems that varied in geometry and spatial structure in order to study cell-to-cell interactions  
306 [42,43; Table 1], but this technology is not readily available to most ecologists.

### 307 *Printing*

308         Once the 3D image has been drafted and edited, and the printer and print materials have  
309 been selected, a test round of printing is necessary before moving to the final round. Printing a  
310 test object makes it possible to identify errors with the 3D image file, compare print materials  
311 and confirm the material choice, and gain an estimate of the amount of time required for printing  
312 *en masse*. After all aspects of the printing project have been approved, the final prints can  
313 proceed. Following printing, various post-processing stages will likely need to occur, such as  
314 removing scaffolding, painting, adding clay, and/or assembling pieces.

### 315 **Results**

316         Here we provide an example of a successful attempt to integrate 3D printing into an  
317 ecological project following the workflow outlined above. We include the obstacles encountered  
318 along the way as a useful case study for other ecologists. Note, we used equipment (scanners and  
319 printers) and expertise from two (out of the four) 3D printing centers at our institution. For  
320 ecologists with fewer onsite resources, online resources and resources at collaborating  
321 institutions may be useful.

322         Clay animal models have long been used in ecological field research to infer predation  
323 rates by free-ranging predators on prey. In this methodology, animal models are constructed  
324 from plasticine modeling clay and then placed in the field for a fixed time period. Because the  
325 clay does not harden, predation attempts leave marks in the clay, making it possible to score  
326 models for evidence of predation. Early work used this method to study how body coloration  
327 affected predation rates in snakes [44,45]. Since then, clay models have been used in predation

328 studies to represent a wide range of taxa including frogs [46], salamanders [47], lizards [48], and  
329 insect larvae [49].

330 In many of these studies, models are constructed by hand either completely or nearly  
331 completely from clay [e.g., 45,47,49,50]. In other studies, silicon molds are made from preserved  
332 specimens, which are then used to make models either directly out of clay [51], or out of plaster  
333 which is then covered with clay [52]. These methods clearly produce models that elicit responses  
334 in predators, however, producing the models in this manner can be time consuming as studies  
335 may use upwards of 100 models. In addition, modifying the models in a precise manner to test  
336 the effects of prey traits on predation is difficult. The repeatability, speed, and precision of 3D  
337 printing make it highly applicable to field studies of predation using models. We first explored  
338 the ease of creating a 3D scan of a preserved lizard specimen, and then used software to modify  
339 its body size. We then tested the durability of two print materials and two model sizes in a field  
340 predation study.

#### 341 *Making the lizard model*

342 We used two methods, a structured light scanner (David SLS-2 3D Scanner, HP Inc.,  
343 Palo Alto, CA, USA) and a laser scanner (NextEngine2020, NextEngine, Inc., Santa Monica,  
344 CA, USA), to make 3D scans of a preserved male *Anolis sagrei* lizard. Structured light scanners  
345 operate by projecting light patterns onto the object being scanned and analyzing the pattern's  
346 deformation with a camera. The laser scanner we used boasts new technology consisting of more  
347 sophisticated algorithms and multiple lasers which scan in parallel, yielding more data points and  
348 an overall more accurate scan. Both scanners are designed to scan 3D objects, but because they  
349 use different technologies to do so, one scanner may be more effective for scanning a particular  
350 object. Regardless of the number of scans or angle of rotation, the structured light scanner's

351 software was not able to converge the multiple scans into a single image of our anole, likely due  
352 to the complexity and high reflectance of the preserved specimen's skin. The laser scanner,  
353 however, was able to produce a digital 3D image of the specimen within about 90 minutes, and  
354 we used this file going forward. The laser scanner was most successful when the lizard specimen  
355 was positioned in a vertical rather than flat manner using an Extra Part Gripper (NextEngine,  
356 Inc., Santa Monica, CA, USA; Figure 2A).

357 We used Maya software (Autodesk, San Rafael, CA, USA; Additional File 2) to edit the  
358 scanned image (Figure 2B) of the lizard specimen to attain three goals. First, to make the lizard  
359 scan possible to print, we had to edit the non-manifold geometry errors that arose due to the  
360 scanning process. Second, we manipulated the size of the lizard to test whether different printing  
361 materials were durable for both large and small prints. The large lizard was 25% larger than the  
362 original (snout vent length = 60 mm). Finally, we added a hollow horseshoe-shaped tube in the  
363 ventral side of the body cavity for looping a small wire through in order to anchor the models to  
364 branches in the field. The final file we used to print the lizards is available from the authors.

#### 365 *Print material and printing*

366 We tested two types of filament print media: plastic (ABS-P430 plastic in ivory,  
367 Stratasys, Eden Prairie, MN, USA) and plastic-wood hybrid (Woodfill by ColorFabb, Belfeld,  
368 the Netherlands). ABS exceeded the Woodfill in cost and perceived durability, yet Woodfill was  
369 a more sustainable option as it is made of 30% recycled wood fibers. During our test print stage,  
370 we learned we needed to add a base to our digital 3D image file for the Woodfill prints because  
371 the scanned image was not flat which made it difficult to print. We did not need to edit it for the  
372 ABS print because the scaffold base dissolved.

373           After we finalized our 3D image files from the test print stage, we printed 10 ABS  
374 models on a Dimension Elite Printer (Stratasys, Eden Prairie, MN, USA) and seven plastic-wood  
375 hybrid models on a BigBox 3D Printer (Chalgrove, UK) (Figure 2C). We had intended to print  
376 equal numbers of each, however, the printer using the Woodfill kept getting jammed and starting  
377 over, and seven was all we could print in the timeframe we had available. The printer jamming  
378 was due in part to the print material and due to errors in the file geometry that were not  
379 adequately resolved during the editing stage. In total, it took about eight hours to print the 10  
380 ABS lizards plus an additional four hours to dissolve the scaffolding. It took nearly five days to  
381 print the seven plastic-wood hybrid models (due to the printer jamming), and the scaffolding  
382 needed to be cut off by hand using an Exacto knife which took about an hour for all seven  
383 models. If the printer had not jammed, it would have taken two hours per model to print.

384           It was quite difficult to thread the narrow floral wire (26 gage, Panacea Products,  
385 Columbus, OH, USA) through the ventral holes in both Woodfill and ABS of models. The tube  
386 we made was curved, and in hindsight it should have been straight through the lizard midsection.  
387 Instead, we wrapped the wire around the midsection of the bodies with two long ends hanging  
388 off the ventral side. We then held the models by the wire and dipped them in melted plasticine  
389 clay (Craft Smart, Irving, TX, USA) to completely cover all parts of the body and the wire  
390 wrapped around the midsection. After the clay solidified (about 30 minutes), we folded the wire  
391 and wrapped each lizard in aluminum foil for transport to the field.

392           In total, our time investment from scanning to printing was relatively low: it took 20  
393 hours from scanning the specimen to our first test print. Additional manipulations to the image  
394 took an additional 40 hours (an undergraduate working 5 hours/week for 2 months). Although  
395 we had to troubleshoot issues with our image and printing, the process was relatively easy due to

396 the resources available at the 3D print centers (namely staff to mentor undergraduate on image  
397 software and troubleshoot printing issues), and that we did not need the surface to be an exact  
398 biological replica because we covered the models with clay.

#### 399 *Field testing lizard models*

400 Lizard models were deployed in developed (residential yard) and natural (national park)  
401 habitats on the island of Curaçao (Dutch Antilles) for 24-48h and then scored for predation. In  
402 both habitat types, models were anchored to tree branches, bushes, or rocks on the ground using  
403 the floral wire. We recorded evidence of predation from likely lizard and avian predators (Figure  
404 2D). There were no differences in predation between ABS and Woodfill models ( $F_{1,30}=0.48$ ,  $P =$   
405  $0.49$ ) or between small and large models ( $F_{1,30}=0.01$ ,  $P = 0.93$ ), yet more models were attacked  
406 in the natural versus developed habitat type ( $F_{1,30}=17.15$ ,  $P < 0.001$ ) (Figure 3). We attribute  
407 these differences in attack rates in habitat types to there being fewer resources available to  
408 predators in natural habitats during the height of the dry season compared to more abundant  
409 resources available in irrigated residential yards. Regardless, both material types were durable to  
410 the field conditions and none of our models experienced any structural problems during the  
411 experiment.

#### 412 *Recommendations for using 3D printed models for field predation studies*

413 Because the Woodfill models were cheaper and just as durable as the less sustainable  
414 ABS models, we would recommend using the Woodfill, or other similar plastics in comparable  
415 future studies, provided that the jamming issues we encountered during printing can be attributed  
416 to geometry errors in our file and not the Woodfill material itself. It should be noted that  
417 although we tested the models in extremely hot ( $>35^{\circ}\text{C}$ ) field conditions, we cannot comment on  
418 the durability of the two materials in rainy or very cold conditions. Initially, we believed the

419 Woodfill would crumble more on the smaller model with narrower appendages, but this was not  
420 the case. Finally, our study took place over a 3-week period. It is possible that over longer time  
421 periods, the Woodfill would not be as durable as the ABS plastic.

## 422 **Discussion**

### 423 *Reduce, Reuse, Recycle*

424 While 3D printing can facilitate ecological research, the use of this technology must be  
425 weighed against its environmental and social costs. In general, 3D printing has the potential to  
426 reduce CO<sub>2</sub> emissions and lead to more sustainable practices in the consumer manufacturing  
427 industry [53], yet there are still many less sustainable aspects to consider. Three-dimensional  
428 printing is much more energy intensive than 2D printing, and the most widely used materials in  
429 3D printing, plastics, are fossil fuel based. Most 3D materials (e.g., plastic filament) are virgin  
430 and not derived from recycled post-consumer products, and if not disposed of and recycled  
431 properly, printed objects can exist in the environment for ages. The plastics used in printing can  
432 be toxic to aquatic organisms, especially resin-based printed objects [54]. The printing process  
433 itself generates extra waste due to printers jamming, misprinted models, and scaffolding  
434 necessary for more complex 3D objects. In addition, printing produces harmful emissions in the  
435 form of ultra-fine particles and volatile organic compounds [55,56], which can be especially  
436 worrisome as many 3D printers are housed in indoor office settings [57]. With respect to the  
437 manufacturing of any plastic item, these negative aspects are not unique to 3D printing, they just  
438 become more obvious when one is directly involved in the manufacturing process. In our  
439 specific case, we chose 3D printed models for the speed at which they could be produced and  
440 their durability as we intend to use them in future experiments. Ecologists planning to

441 incorporate 3D printing in research should strongly consider the negative impacts associated with  
442 3D printing compared to the impacts of creating objects via other methods or not at all.

443         There are promising advances in the sustainability of 3D printing materials. Materials  
444 scientists are developing a range of filaments that are biodegradable, compostable, and made  
445 from recycled materials. For example, Eco-Filaments, such as WillowFlex (BioInspiration,  
446 Eberswalde, Germany), are made from plant-based resources and are completely compostable,  
447 even in residential compost bins. Other filament choices are made from recycled plastics like car  
448 dashboards, PET bottles, and potato chip bags (3D Brooklyn, Brooklyn, NY, USA; Refil,  
449 Rotterdam, the Netherlands). In fact, the cost of generating recycled plastic filament is often less  
450 than filament made from raw materials, prompting the establishment of a fair trade market for  
451 used plastic collected by waste pickers in the developing world (e.g., Protoprint Solutions, Prune,  
452 India) [58]. Non-plastic recycled filament options exists, such as filament made from the waste  
453 products of beer, coffee, and hemp production processes (3DFUEL, Fargo, ND, USA) as well as  
454 wood pulp [59]. Finally, because common print materials such as ABS plastic are not  
455 biodegradable or recyclable in municipal recycling centers, machines have been developed to  
456 recycle these plastics directly at the printing site [60]. These machines grind old prints and melt  
457 them into new filament that can be reused for printing (e.g. Filastruder, Snellville, GA, USA).  
458 Across sustainable options for print materials, we can attest to the durability of Woodfill for  
459 applications comparable to ours. For ecologists considering other sustainable print materials,  
460 most of these companies readily provide information about the durability of their products.

461         We stress that all 3D printing projects in ecological research should reduce, reuse, and  
462 recycle: *Reduce* the amount printed and the use of toxic print materials; *Reuse* printed objects  
463 and use materials made from post-consumer, waste materials; and *Recycle* printed objects by

464 choosing materials that can be easily recycled, composted, or that are biodegradable. Planning a  
465 print job (Fig. 1) requires both careful estimation of the minimum number of replicates to print  
466 and smart design of geometry that minimizes or eliminates scaffolding, as scaffolding is usually  
467 discarded. Printing should be performed in well-ventilated environments where airborne toxins  
468 do not accumulate and harm personnel. The environmental toxicity of objects should be reduced  
469 by choosing materials with low toxic potential and reducing the toxicity of materials post-print.  
470 For example, exposure of resin-based printed objects to intense UV light can reduce their  
471 toxicity to aquatic organisms [54]. Printed objects should be reused in research as much as  
472 possible to avoid repeat printing, and print materials made from recycled material or materials  
473 that are recyclable or compostable should be used when possible. While most ecologists will not  
474 invest in their own 3D printing equipment and instead employ general-use academic (e.g.,  
475 library) or commercial facilities, these environmental concerns can be communicated to the  
476 printing facilities so that they might adopt sustainable practices in their 3D printing for research.

## 477 **Conclusions**

478 In conclusion, 3D printing technology has the promise to reduce the time and cost  
479 invested in creating custom materials used in ecological research, while at the same time  
480 increasing the ease at which collaborations occur within and outside the scientific community.  
481 Although there is a learning curve for developing 3D image files, there are ample online libraries  
482 of 3D files, plus tech savvy students and 3D printing center staff can be extremely helpful.  
483 Recent advances in print materials may reduce the footprint associated with this new technology.  
484 Overall, as with any new technology, ecologists must weigh the costs in terms of time and  
485 monetary investments into developing usable 3D materials for research versus other methods of  
486 generating those materials. If ecologists are in the position to commit the initial investment in

487 securing printing resources and navigating the technological learning curve, the resulting ability  
488 to implement 3D printing into future studies could save time and money on the long term.

489 **Declarations**

490 **Ethics approval**

491 All work conducted involving live animals was in accordance with the Institutional Animal Care  
492 and Use Committee at Temple University (IACUC protocol #4614).

493 **Consent for Publication**

494 Not applicable

495 **Availability of data and materials**

496 The datasets used and/or analysed during the current study are available from the corresponding  
497 author on reasonable request.

498 **Competing interests**

499 The authors declare that they have no competing interests

500 **Funding**

501 This work was supported by funds from the Netherlands Organization for Scientific Research  
502 (858.14.040) and Temple University.

503 **Author Contributions**

504 JB and MH conceived of and designed the study; JB, BW, and MH developed the workflow; BW  
505 tested the workflow and designed the 3D model; JB and MH conducted the field experiment; JB,  
506 BW, STH, and MH wrote the manuscript and provided editorial advice. All authors read and  
507 approved the final manuscript.

508 **Acknowledgements**

509 We thank J. Hample from the Digital Scholarship Center, S. Campbell from the Digital  
510 Fabrication Studio, and C. Denison from the Health Sciences Library Print Center all at Temple

511 University for assistance with scanning and printing the lizard models. We thank M. Vermeij and  
512 S. Berendse from the Carmabi Foundation for logistical support in Curaçao.

513 **Additional Files**

514 **Additional File 1.** Software for designing, modifying, and analyzing 3D files

515 **Additional File 2.** Online libraries of 3D imagery relevant for ecological research (as of 2017)

516

517

518

519 **References**

520 1. Small RJ, Rusch DH. Backpacks vs. Ponchos: Survival and movements of radio-marked ruffed grouse.

521 *Wildlife Society Bulletin* (1973-2006). 1985;13:163–5.

522 2. Reiter J, Curio E, Tacud B, Urbina H, Geronimo F. Tracking bat-dispersed seeds using fluorescent

523 pigment. *Biotropica*. 2006;38:64–8.

524 3. Xiao Z, Jansen PA, Zhang Z. Using seed-tagging methods for assessing post-dispersal seed fate in

525 rodent-dispersed trees. *Forest Ecology and Management*. 2006;223:18–23.

526 4. Patrick LB, Hansen A. Comparing ramp and pitfall traps for capturing wandering spiders. *Journal of*

527 *Arachnology*. 2013;41:404–406.

528 5. Quinn H, Jones JP. Squeeze box technique for measuring snakes. *Herpetol Rev*. 1974;5:35.

529 6. Karraker NE. A new method for estimating clutch sizes of ambystomatid salamanders and ranid frogs:

530 *Introducing the ovagram*. *Herpetological Review*. 2007;38:46–8.

531 7. Peterson CR, Dorcas ME. Automated data acquisition. *Measuring and monitoring biological diversity:*

532 *standard methods for amphibians*. Washington, D. C.: Smithsonian Institution; 1994. p. 47–57.

533 8. Pauli JN, Hamilton MB, Crain EB, Buskirk SW. A single-sampling hair trap for mesocarnivores.

534 *Journal of Wildlife Management*. 2008;72:1650–2.

- 535 9. Conner BP, Manogharan GP, Martof AN, Rodomsky LM, Rodomsky CM, Jordan DC, et al. Making  
536 sense of 3-D printing: Creating a map of additive manufacturing products and services. *Additive*  
537 *Manufacturing*. 2014;1–4:64–76.
- 538 10. Mironov V, Kasyanov V, Drake C, Markwald RR. Organ printing: promises and challenges.  
539 *Regenerative Medicine*. 2008;3:93–103.
- 540 11. Domingue MJ, Pulsifer DP, Lakhtakia A, Berkebile J, Steiner KC, Lelito JP, et al. Detecting emerald  
541 ash borers (*Agrilus planipennis*) using branch traps baited with 3D-printed beetle decoys. *Journal of Pest*  
542 *Science*. 2015;88:267–79.
- 543 12. Watson CM, Francis GR. Three dimensional printing as an effective method of producing  
544 anatomically accurate models for studies in thermal ecology. *Journal of Thermal Biology*. 2015;51:42–6.
- 545 13. Stadler AT, Vihar B, Günther M, Huemer M, Riedl M, Shamiyeh S, et al. Adaptation to life in aeolian  
546 sand: how the sandfish lizard, *Scincus scincus*, prevents sand particles from entering its lungs. *Journal of*  
547 *Experimental Biology*. 2016;219:3597–604.
- 548 14. Bokhorst E van, Kat R de, Elsinga GE, Lentink D. Feather roughness reduces flow separation during  
549 low Reynolds number glides of swifts. *Journal of Experimental Biology*. 2015;218:3179–91.
- 550 15. Vanderelst D, Peremans H, Razak NA, Verstraelen E, Dimitriadis G. The aerodynamic cost of head  
551 morphology in bats: Maybe not as bad as it seems. *PLOS ONE*. 2015;10:e0118545.
- 552 16. Germann DP, Schatz W, Hotz PE. Artificial Bivalves – The Biomimetics of Underwater Burrowing.  
553 *Procedia Computer Science*. 2011;7:169–72.
- 554 17. Moore JM, Clark AJ, McKinley PK. Evolution of station keeping as a response to flows in an aquatic  
555 robot. *Proceedings of the 15th annual conference on Genetic and evolutionary computation [Internet]*.  
556 *ACM*; 2013 [cited 2016 Nov 20]. p. 239–246. Available from: <http://dl.acm.org/citation.cfm?id=2463402>
- 557 18. Clark AJ, Wang J, Tan X, McKinley PK. Balancing performance and efficiency in a robotic fish with  
558 evolutionary multiobjective optimization. *2014 IEEE International Conference on Evolvable Systems*  
559 *(ICES)*. 2014. p. 227–34.

- 560 19. Ziegler A, Menze B. Accelerated Acquisition, Visualization, and Analysis of Zoo-Anatomical Data.  
561 Computation for Humanity [Internet]. Boca Raton: CRC Press; 2013 [cited 2016 Nov 20]. p. 235–64.  
562 Available from: <http://www.crcnetbase.com/doi/abs/10.1201/b15617-14>
- 563 20. Mitsopoulou V, Michailidis D, Theodorou E, Isidorou S, Roussiakis S, Vasilopoulos T, et al.  
564 Digitizing, modelling and 3D printing of skeletal digital models of *Palaeoloxodon tiliensis* (Tilos,  
565 Dodecanese, Greece). *Quaternary International*. 2015;379:4–13.
- 566 21. Niven L, Steele TE, Finke H, Gernat T, Hublin J-J. Virtual skeletons: using a structured light scanner  
567 to create a 3D faunal comparative collection. *Journal of Archaeological Science*. 2009;36:2018–23.
- 568 22. Raupach MJ, Amann R, Wheeler QD, Roos C. The application of “-omics” technologies for the  
569 classification and identification of animals. *Org Divers Evol*. 2016;16:1–12.
- 570 23. Lak M, Fleck G, Azar D, Engel Fls MS, Kaddumi HF, Neraudeau D, et al. Phase contrast X-ray  
571 synchrotron microtomography and the oldest damselflies in amber (Odonata: Zygoptera:  
572 Hemiphlebiidae). *Zoological Journal of the Linnean Society*. 2009;156:913–23.
- 573 24. Bokor J, Broo J, Mahoney J. Using fossil teeth to study the evolution of horses in response to a  
574 changing climate. *The American Biology Teacher*. 2016;78:166–9.
- 575 25. Igic B, Nunez V, Voss HU, Croston R, Aidala Z, López AV, et al. Using 3D printed eggs to examine  
576 the egg-rejection behaviour of wild birds. *PeerJ*. 2015;3:e965.
- 577 26. Bartolini T, Mwaffo V, Showler A, Macrì S, Butail S, Porfiri M. Zebrafish response to 3D printed  
578 shoals of conspecifics: the effect of body size. *Bioinspiration & Biomimetics*. 2016;11:026003.
- 579 27. Thomson JD, Draguleasa MA, Tan MG. Flowers with caffeinated nectar receive more pollination.  
580 *Arthropod-Plant Interactions*. 2015;9:1–7.
- 581 28. Campos EO, Bradshaw HD, Daniel TL. Shape matters: corolla curvature improves nectar discovery in  
582 the hawkmoth *Manduca sexta*. *Funct Ecol*. 2015;29:462–8.
- 583 29. Policha T, Davis A, Barnadas M, Dentinger BTM, Raguso RA, Roy BA. Disentangling visual and  
584 olfactory signals in mushroom-mimicking *Dracula* orchids using realistic three-dimensional printed  
585 flowers. *New Phytol*. 2016;210:1058–71.

- 586 30. Otten W, Pajor R, Schmidt S, Baveye PC, Hague R, Falconer RE. Combining X-ray CT and 3D  
587 printing technology to produce microcosms with replicable, complex pore geometries. *Soil Biology and*  
588 *Biochemistry*. 2012;51:53–5.
- 589 31. Dal Ferro N, Morari F. From real soils to 3D-printed soils: Reproduction of complex pore network at  
590 the real size in a silty-loam soil. *Soil Science Society of America Journal*. 2015;79:1008–17.
- 591 32. Bertin S, Friedrich H, Delmas P, Chan E, Gimel'farb G. Dem quality assessment with a 3D printed  
592 gravel bed applied to stereo photogrammetry. *The Photogrammetric Record*. 2014;29:241–64.
- 593 33. Hesterberg S. Three-dimensional interstitial space mediates predator foraging success in different  
594 spatial arrangements. Masters Thesis. [Internet] [Masters Thesis]. [Tampa, Florida, USA]: University of  
595 South Florida; 2016. Available from: <http://scholarcommons.usf.edu/etd/6096>
- 596 34. Mohammed JS. Applications of 3D printing technologies in oceanography. *Methods in*  
597 *Oceanography*. 2016;17:97–117.
- 598 35. Berry D, Selby RD, Horvath JC, Cameron RH, Porqueras D, Stouthamer R. A modular system of 3D  
599 printed emergence traps for studying the biology of shot hole borers and other scolytinae. *J Econ*  
600 *Entomol*. 2016;109:969–72.
- 601 36. Bennett A, Barrett D, Preston V, Woo J, Chandra S, Diggins D, et al. Autonomous Vehicles for  
602 Remote Sample Collection Enabling Marine Research. *Proc. IEEE/MTS OCEANS*. Genova, Italy; 2015.  
603 p. 8.
- 604 37. Borer ET, Harpole WS, Adler PB, Lind EM, Orrock JL, Seabloom EW, et al. Finding generality in  
605 ecology: a model for globally distributed experiments. *Methods Ecol Evol*. 2014;5:65–73.
- 606 38. Newman G, Wiggins A, Crall A, Graham E, Newman S, Crowston K. The future of citizen science:  
607 emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment*. 2012;10:298–  
608 304.
- 609 39. Rochman D, Luna ED. Prototyping the complex biological form of the beetle *Deltotichilum lobipes* via  
610 2D geometric morphometrics landmarks and descriptive geometry for 3D printing. *Computer-Aided*  
611 *Design and Applications*. 2017;14:107–16.

- 612 40. Ruberto T, Polverino G, Porfiri M. How different is a 3D-printed replica from a conspecific in the  
613 eyes of a zebrafish?: How does a zebrafish see a replica? *Journal of the Experimental Analysis of*  
614 *Behavior*. 2017;107:279–93.
- 615 41. Tabone MD, Cregg JJ, Beckman EJ, Landis AE. Sustainability Metrics: Life Cycle Assessment and  
616 Green Design in Polymers. *Environ. Sci. Technol*. 2010;44:8264–9.
- 617 42. Connell JL, Ritschdorff ET, Whiteley M, Shear JB. 3D printing of microscopic bacterial  
618 communities. *PNAS*. 2013;110:18380–5.
- 619 43. Connell JL, Kim J, Shear JB, Bard AJ, Whiteley M. Real-time monitoring of quorum sensing in 3D-  
620 printed bacterial aggregates using scanning electrochemical microscopy. *PNAS*. 2014;111:18255–60.
- 621 44. Madsen T. Are juvenile grass snakes, *Natrix-Natrix*, aposematically colored. *Oikos*. 1987;48:265–7.
- 622 45. Brodie E. Differential avoidance of coral snake banded patterns by free-ranging avian predators in  
623 Costa Rica. *Evolution*. 1993;47:227–35.
- 624 46. Flores EE, Stevens M, Moore AJ, Rowland HM, Blount JD. Body size but not warning signal  
625 luminance influences predation risk in recently metamorphosed poison frogs. *Ecology and Evolution*.  
626 2015;5:4603–16.
- 627 47. Kraemer AC, Serb JM, Adams DC. Both novelty and conspicuousness influence selection by  
628 mammalian predators on the colour pattern of *Plethodon cinereus* (Urodela: Plethodontidae). *Biological*  
629 *Journal of the Linnean Society*. 2016;118:889–900.
- 630 48. Sato CF, Wood JT, Schroder M, Green K, Osborne WS, Michael DR, et al. An experiment to test key  
631 hypotheses of the drivers of reptile distribution in subalpine ski resorts. *J Appl Ecol*. 2014;51:13–22.
- 632 49. Peisley RK, Saunders ME, Luck GW. Cost-benefit trade-offs of bird activity in apple orchards. *PeerJ*.  
633 2016;4:e2179.
- 634 50. Vazquez B, Hilje B. How habitat type, sex, and body region influence predatory attacks on *Norops*  
635 lizards in a pre-montane wet forest in Costa Rica: an approach using clay models. *Herpetology Notes*.  
636 2015;8:205–12.

- 637 51. Yeager J, Wooten C, Summers K. A new technique for the production of large numbers of clay  
638 models for field studies of predation. *Herpetol Rev.* 2011;42:357–9.
- 639 52. Gifford ME, Herrel A, Mahler DL. The evolution of locomotor morphology, performance, and anti-  
640 predator behaviour among populations of *Leiocephalus* lizards from the Dominican Republic. *Biological*  
641 *Journal of the Linnean Society.* 2008;93:445–56.
- 642 53. Gebler M, Schoot Uiterkamp AJM, Visser C. A global sustainability perspective on 3D printing  
643 technologies. *Energy Policy.* 2014;74:158–67.
- 644 54. Oskui SM, Diamante G, Liao C, Shi W, Gan J, Schlenk D, et al. Assessing and Reducing the Toxicity  
645 of 3D-Printed Parts. *Environmental Science & Technology Letters.* 2016;3:1–6.
- 646 55. Azimi P, Zhao D, Pouzet C, Crain NE, Stephens B. Emissions of ultrafine particles and volatile  
647 organic compounds from commercially available desktop three-dimensional printers with multiple  
648 filaments. *Environmental Science & Technology.* 2016;50:1260–8.
- 649 56. Yi J, LeBouf RF, Duling MG, Nurkiewicz T, Chen BT, Schwegler-Berry D, et al. Emission of  
650 particulate matter from a desktop three-dimensional (3D) printer. *Journal of Toxicology and*  
651 *Environmental Health, Part A.* 2016;79:453–65.
- 652 57. Steinle P. Characterization of emissions from a desktop 3D printer and indoor air measurements in  
653 office settings. *Journal of Occupational and Environmental Hygiene.* 2016;13:121–32.
- 654 58. Feeley S., Wijnen B, Pearce JM. Evaluation of potential fair trade standards for an ethical 3-D  
655 printing filament. *Journal of Sustainable Development.* 2014;7:1–12.
- 656 59. Gardan J, Roucoules L. 3D printing device for numerical control machine and wood deposition. Julien  
657 Gardan Int. *Journal of Engineering Research and Applications.* 2015;4:123–31.
- 658 60. Baechler C, Matthew DeVuono, Joshua M. Pearce. Distributed recycling of waste polymer into  
659 RepRap feedstock. *Rapid Prototyping Journal.* 2013;19:118–25.
- 660 61. Cianca V, Bartolini T, Porfiri M, Macrì S. A robotics-based behavioral paradigm to measure anxiety-  
661 related responses in zebrafish. *PLOS ONE.* 2013;8:e69661.
- 662

**Table 1:** Ecological studies that have used 3D printing

Research Topic	Taxa	Objects Printed	Print Medium	Sample Size <sup>a</sup>	Reference
<i>Behavioral Ecology</i>					
Egg rejection behavior in context of brood parasitism	brown-headed cowbird ( <i>Molothrus ater</i> )	cowbird eggs that varied in size/shape, then painted different colors	“white strong and flexible plastic, polished”	80	[25]
Effect of corolla shape on pollinator behavior	Hawkmoth ( <i>Manduca sexta</i> )	flowers that varied in corolla shape based on specific mathematical parameters	Acrylonitrile butadiene styrene (ABS) plastic	NR	[28]
Effects of visual and olfactory floral traits in attracting pollinators	Mushroom-mimicking orchid ( <i>Dracula lafleurii</i> )	molds to make silicon flowers	Cyanoacrylate impregnated gypsum	NR	[29]
Effect of nectar caffeine concentrations on pollination service	Bumble Bees ( <i>Bombus impatiens</i> )	structures that functioned like corollas over glass jars containing artificial nectar	Plastic (type non-specified)	Min. 18	[27]
Social behavior of zebrafish in response to varying stimuli	Zebrafish ( <i>Danio rerio</i> )	predatory fish model robot	ABS plastic	1	[61]
		shoals comprising 3 zebrafish that varied in body size plus anchoring materials	ABS plastic	4 shoals	[26]
		biologically-inspired zebrafish replica	ABS plastic	1	[40]
Evaluation of 3D printing as suitable method for field predation model studies	Brown anole ( <i>Anolis sagrei</i> )	lizard models using 2 print media, covered in clay, and field-tested for predation	ABS plastic, plastic-wood hybrid filament	17	This study

*Thermal Ecology*

Comparing thermodynamics of 3D printed and copper lizard models

Texas horned lizard  
(*Phrynosoma cornutum*)

thermal models of lizards

ABS plastic

10

[12]

*Tools – Experimental arenas*

Evaluation of 3D printed soil as suitable for fungal colonization

Plant pathogenic fungus  
(*Rhizoctonia solani*)

artificial soil from 3D scans of soil with varying micropore structure

Nylon 12

10

[30]

Comparing hydraulic properties of 3D printed soil relative to real soil

Soil

artificial soil from 3D scans of soil

Resin (Visijet  
Crystal EX  
200 Plastic  
Material)

14

[31]

Microscale bacterial cell-cell interactions

*Pseudomonas aeruginosa* and  
*Staphylococcus aureus*

“designer” bacterial ecosystems that vary in size, geometry and spatial distance with exact starting quantities of *P. aeruginosa* and *S. aureus*

Gelatin

NR

[42,43]

Effect of interstitial space on predator-prey interactions

Blue crab (*Callinectes sapidus*) and Mud crab (*Eurypanopeus depressus*)

oyster shells aggregated into artificial reefs that varied in interstitial space configuration

Polylactic or  
ABS plastic

NR

[33]

*Tools – Sampling Equipment*

Collecting unobtrusive biological samples from whales

Southern right, humpback and sperm whales

components to build an unmanned surface vehicle for oceanographic research (*SnotBot*)

ABS plastic  
and nylon

1

[36]

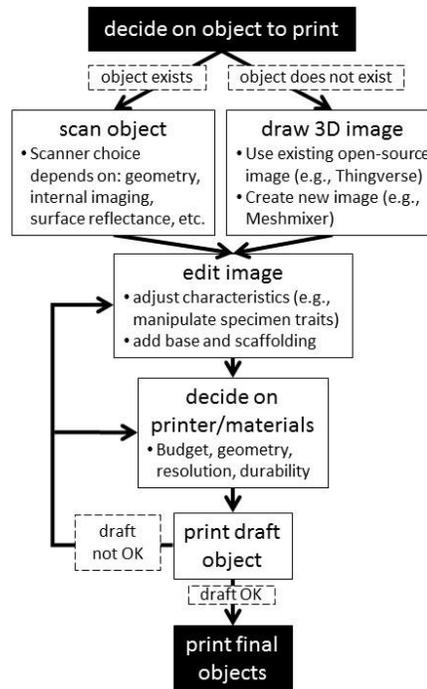
Tools for studying the impact of ambrosia beetles on trees	Shot hole borer beetle ( <i>Euwallacea fornicatus</i> )	components for entry devices and emergence traps	ABS plastic	15	[35]
Testing decoys vs real beetles to enhance trap capture rates	Emerald ash borer beetle ( <i>Agrilus planipennis</i> )	beetle decoy to use on traps	ABS plastic	300	[11]

---

<sup>a</sup>NR = Not reported

664 **Figure Legends**

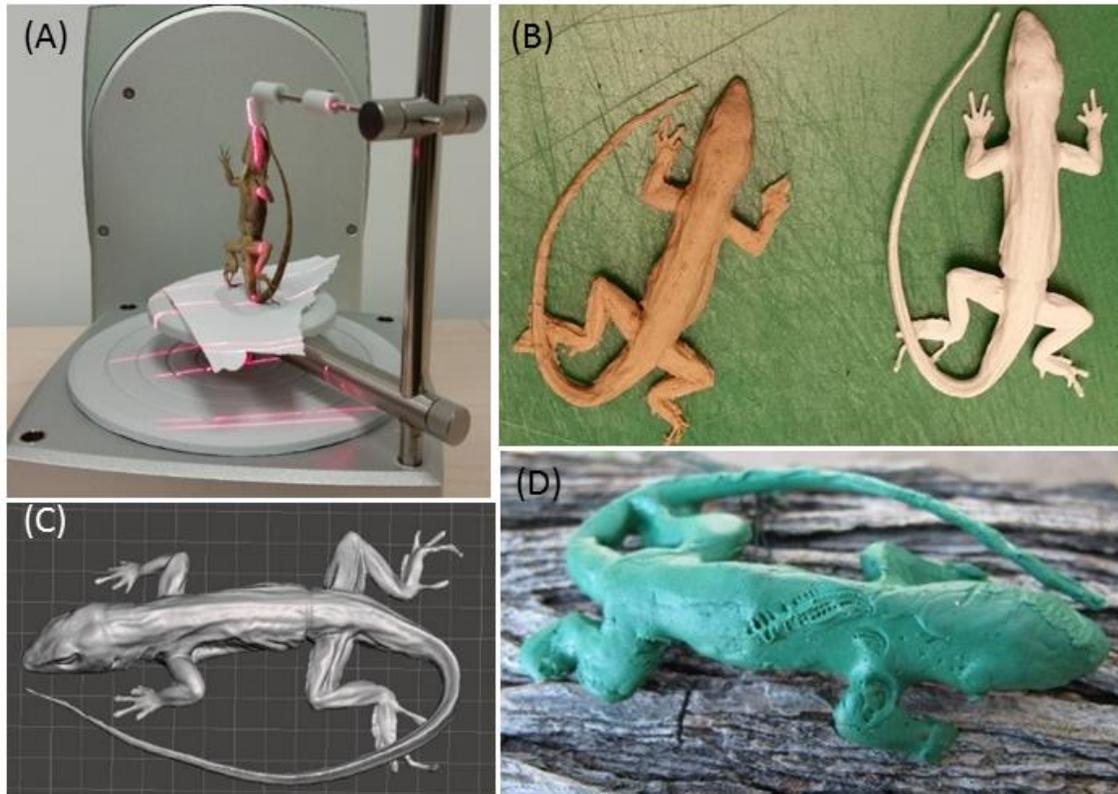
666 **Fig. 1** Workflow illustrating steps for integrating 3D printing in ecological research



668

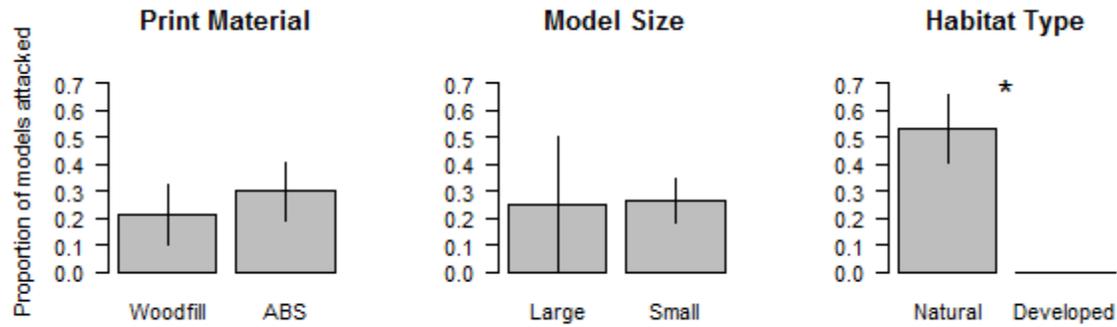
670

**Fig. 2** Construction of a 3D printed lizard predation model a) Successful laser scanning setup of  
672 preserved brown anole (*Anolis sagrei*) specimen in vertical orientation; b) 3D image of scanned  
anole viewed in Meshmixer software and later edited in Maya; c) 3D printed plastic-wood hybrid  
674 (left) and ABS plastic (right) anole models; d) clay covered model on a branch in the field with  
bite marks likely from a lizard predator (*Cnemidophorus murinus murinus*).



676

678 **Fig. 3** Proportion of clay-covered 3D printed models attacked during field predation trials. Bars are means  
+/- one standard error; \* indicates significantly different means at  $P < 0.01$ .



680