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1 A wide range of applications and innovations from Ecological and Environmental
2 research

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26 27 **Abstract**

28 Research in Ecology and environmental sciences is rapidly becoming a source
29 of applications and innovations, with increasing diversity. These innovations concern
30 a large range of fields, from blue biotechnology to socioecosystem management. The
31 aim of the present review is to explore this diversity by describing some of the most
32 recent studies in Ecology and environmental science that have led to environmental,
33 societal, and industrial applications. Past and present research in Ecology and
34 environmental science proves to be an essential means for creating awareness

35 about global threats (e.g. climate change) and for guiding national and local
36 authorities (e.g. ecosystem management). Future research is likely to be even more
37 proactive toward societal and environmental challenges, by providing technological
38 innovations and concrete solutions to ensure both nature conservation and its
39 exploitation.

40

41 La diversité des innovations issues des Sciences de l'Écologie et de l'Environnement

42

43 **Résumé**

44 La recherche en Ecologie et en Sciences de l'Environnement est une source
45 d'applications et d'innovations très diversifiées. L'objectif de cet article est d'explorer
46 cette diversité en décrivant certaines des études les plus récentes qui ont conduit à
47 des applications environnementales, sociétales ou industrielles. En effet, au-delà de
48 l'utilisation des interactions biologiques pour lutter contre l'invasion d'organismes
49 indésirables par exemple, les organismes microscopiques ou macroscopiques sont
50 de plus en plus utilisés comme matières premières ou produits d'intérêt
51 biotechnologique, utilisant soit des organismes entiers, soit des molécules qui en
52 sont extraites et purifiées. Parce que les animaux, les plantes et les micro-
53 organismes influencent fortement leur environnement et ses propriétés, certains sont
54 utilisés dans des processus éco-techniques pour la restauration ou la gestion
55 écologique des terres, des rivières, des lacs, des océans et des villes. La
56 compréhension approfondie du fonctionnement des (socio)écosystèmes et des
57 services (socio)écosystémiques associés conduit également à proposer de nouvelles
58 implémentations d'indicateurs de gestion environnementale. Les recherches passées
59 et présentes en Ecologie et en Sciences de l'Environnement se révèlent être
60 essentielles pour sensibiliser et guider la société civile et les autorités publiques. Les
61 recherches futures seront probablement encore plus proactives face aux défis
62 sociétaux et environnementaux, en apportant des solutions concrètes pour assurer à
63 la fois la conservation de la nature et son exploitation.

64

65 Key words: Research, Sustainable development, Technology, Biomimicry,
66 Conservation

67 Mots clés: Recherche, Développement durable, Technologie, Bioinspiration,
68 Conservation

69

70 **Introduction**

71

72 Decades of interdisciplinary research in the fields of Ecology and Environment,
73 based on observations, experiments and modelling, evidenced local and global
74 threats to biodiversity and habitats, alerting the public opinion and governments. The
75 origin and impacts of global changes, such as water eutrophication, plastic and toxic
76 pollutions, invasive species, or the emergence of pathogens, are intensively
77 investigated, leading to innovative mitigation solutions, new ecosystem management
78 protocols and government laws.

79 Furthermore, human demography and its expansion impose intense pressure
80 on food and water resources, as do cities and land use. New paradigms are thus
81 required for more sustainable human development, where economics become
82 compatible with societal and environmental concerns. Besides its contribution to
83 recent political, societal and industrial awareness concerning threats to our
84 environment, research in Ecology and Environment is also the source of applications
85 and innovations in various fields. This is illustrated, for example, with the
86 development of new food production systems, such as agroforestry, organic farming,
87 permaculture, and integrated multitrophic aquaculture. These are all based on
88 ecological concepts, which grant the benefits of biodiversity, interactions between
89 organisms and biological recycling processes.

90 Bio-inspiration appears to be one more key-stone concept that encounters
91 much enthusiasm from both scientific and industrial communities, and stimulates a
92 large spectrum of innovative initiatives. Beyond nature inspiration, research in
93 synthetic biology is harnessing the power of nature to solve problems in medicine,
94 manufacturing, and agriculture. Some want to find environmentally sustainable ways
95 to mimic natural resources. There are those who want to elaborate new kinds of
96 medical treatments for deadly diseases. Others again want to grow more productive
97 crops. The promises of such work are vast. Synthetic biology is an interdisciplinary
98 field that aims to design and make biological parts and systems. It will need to
99 become an engineering discipline to take its place in future advanced manufacturing.

100 Within the academic community, studies in Ecology and Environment leading
101 to applications are gaining in popularity, as shown by the high rank (3rd) within
102 median journal impact factors recorded for the “Green and sustainable science and

103 technology” journal category, out of 236 journal categories from the Journal of
104 Citation Report. This journal category covers 41 different journals focussing on
105 fundamental and applied research on green and sustainable science and technology,
106 including green chemistry; green nanotechnology; green building; renewable and
107 green materials; sustainable processing and engineering; sustainable policy,
108 management and development; environmental and agricultural sustainability;
109 renewable and sustainable energy; and innovative technologies that reduce or
110 eliminate damage to health and the environment. During these last 30 years,
111 research areas such as mathematics, business economics or technology provided
112 increasing and significant contributions to applied Ecology and Environment studies.
113 Interdisciplinary research has always been required for resolving fundamental
114 ecological or environmental questions, and even more so when applications are
115 proposed. Because of the vast number of potential combinations of different scientific
116 disciplines (biology, physics, chemistry, mathematics, computer science, geography,
117 social sciences, politics, economy, etc.), the diversity of applications is widespread
118 and may concern a large range of fields from blue biotechnology to management.

119 The present article aims to explore this diversity by illustrating how studies
120 investigating the characteristics and dynamics of organisms, or of whole (socio)-
121 ecosystems, can lead to environmental, societal and industrial applications. Some
122 examples will be provided, based on recently published reports which were brought
123 to the present authors’ knowledge, and which encompass a wide range of research
124 topics in Ecology and Environment, from organism characteristics to human-nature
125 interactions¹.

126 In order to highlight their diversity, as well as their importance, the following sections
127 will provide descriptions of certain applications, based on the observation of a single
128 organism or of a population, organism or organism-environment interactions, and
129 socio-ecological systems.

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¹ This article is the result of the reflection carried out by the collective of the INEE-CNRS Multidisciplinary Thematic Network RTP “*Innovations in Ecology and Environmental Sciences*”, which follows the INEE-CNRS days on Future Scientific Challenges organized in 2017 (22-24 February, Bordeaux, France).

133 **Applications based on the characteristics of a single organism or population**

134

135 Historically, observations of living organisms in their natural or experimentally
136 simulated ecosystem, through physiological, ecological and modelling approaches,
137 have led to elaborating ecological concepts, biogeochemical budgets, assessments
138 of exploited resources and human impacts on ecosystems. More recently, studies on
139 organisms have generated innovative technologies for human welfare or wildlife
140 conservation.

141 Indeed, progress in research concerning the new-found functions of organisms
142 or the compounds they produce, has led to microscopic or macroscopic organisms
143 being mimicked. For example, the ability of viruses to infect specific cells within host
144 organisms, to replicate, destroy the cells, and spread from cell to cell in infectious
145 cycles, has inspired synthetic designs of various delivery vehicles in the human body.
146 Lee et al (2008) designed a pH-sensitive nanogel consisting of a hydrophobic
147 copolymer core and two layers of hydrophilic shells. This nanogel evidenced
148 behaviours similar to those of a virus, where it actively infects tumour cells in a
149 receptor-dependent manner, then destroys the cells, before migrating to
150 neighbouring cells and repeating the process anew. Another example is proposed
151 from the ability of the desert ant *Cataglyphis* to use polarized sky light and to
152 integrate its speed and steps through its eyes, that can be mimicked in order to
153 propose an innovative way to travel without using GPS (Dupeyroux et al 2019).

154 Organisms can also be used as raw materials or products of biotechnological
155 interest, using either whole organisms or extractions of purified active molecules.
156 Using the natural giant extracellular polymeric haemoglobin of the polychaete annelid
157 *Arenicola marina* as a blood substitute (Rousselot et al 2006) is one of the current
158 promising findings in the domain of human health using natural organisms (**BOX 1**).
159 Microorganisms are also known to produce promising molecules such as
160 expolysaccharides, released by microalgae, which evidence significant antitumor
161 effects in the treatment of human colon cancer cells (Zhang et al 2019).

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167 **BOX 1:** Hemarina is a company founded in 2007 and specialized in the development
168 of universal therapeutic oxygen carriers based on the properties of Lugworm
169 (*Arenicola marina*) hemoglobin. The prospects for therapeutic applications are
170 immense because this molecule is a technological platform; it can be used wherever
171 oxygen is involved and potentially at all levels of the living organism (cell, tissue,
172 organ and organism). As a result, all ischemic diseases (resulting from low blood flow
173 and oxygen deficiency) are potential pathways for development.
174 <https://www.hemarina.com/>



175
176 © Mathieu Le Gall

177 Isolating organisms that are well-adapted to a specific environment because of
178 their unique metabolic or ecological abilities is of particular interest. For instance, by
179 screening natural microbial communities exposed to Poly-ethylene terephthalate (i.e.
180 PET or plastics) in their environment, Yoshida et al (2016) isolated a novel
181 bacterium, *Ideonella sakaiensis*, that can use PET as its major energy and carbon
182 source, opening future perspectives for the biological deconstruction and upcycling of
183 mixed plastics. Isolating the *Pasteuralla multocida* bacteria from a dead darkmantled
184 sooty albatross chick is another example. In this case, the bacteria species was

185 successfully used in a specific tailored vaccine, testing its ability to protect albatross
186 chicks from avian cholera mortality in the field (Bourret et al 2018). Such autogenous
187 vaccines, based on a field strain, could be a key tool to effectively protect
188 endangered populations from disease outbreaks.

189 In addition to detailing their intrinsic characteristics, the in-depth observation of
190 organism dynamics in their environment is essential for understanding their
191 behaviour, and for providing essential information on their controlling growth factors
192 as well. For example, mosquitoes partly rely on olfaction, using it to sense volatiles
193 produced by aquatic microbes, which together with plant detritus serve as food for
194 the larvae. In a recent study, Melo et al (2020) found that the yellow fever mosquito
195 *Aedes aegypti* detects, with a high degree of sensitivity, geosmin produced by
196 cyanobacteria species that typically live in a eutrophic aquatic ecosystem. These
197 authors also showed that geosmin-baited traps held an increased number of eggs in
198 comparison to control traps. Because the distinct odour of geosmin is responsible for
199 the earthy smell of beetroots, the authors successfully used an extract of beetroot
200 peel as bait in traps and provided an innovative method for trapping and potentially
201 controlling *Aedes aegypti*.

202 Biology is an astonishing builder. The ability to exploit this amazing building
203 capacity is now being accelerated by the new field of engineering biology, which
204 applies engineering principles such as standardization, modularization and
205 robustness, to the genetic engineering of complex living systems for specific
206 applications. Very recently, Moffat et al (2021) demonstrated the identification of
207 bacterial genes associated with the growth inhibition of a plant pathogen, using
208 automated high-throughput antagonistic bacterial assays with the accelerated
209 screening of thousands of mutants. The development of such robotic workflows and
210 technology platforms, called biofoundries, has induced an acceleration of prototyping
211 biological designs for synthetic biology applications.

212 Studies looking at organism development and behaviour also provide essential
213 information concerning their habitats, and on the physical integrity, quality,
214 habitability and vulnerability of the environment. For example, free viruses spread in
215 ground waters, and are easily transported through pores, tending to follow fast
216 preferential flow pathways as particles with a minimal matrix. Hun et al (2010)
217 followed the presence of infectious viruses from wastewaters to municipal water-
218 supply wells, and showed a relation between wastewater tracers and virus

219 occurrence, over a sufficient time period. The ability of a virus tracing approach to
220 characterize travel times in high-groundwater velocity settings provides insight which
221 was not available using standard hydrogeological approaches. Regarding
222 endangered organisms, Bisson et al. (2011) used tiny heart-rate transmitters in
223 endangered songbirds (*Vireo atricapilla*) to show that black-capped vireos quickly
224 acclimate to a limited amount of human disturbance (e.g., recreational activities near
225 wildlife habitat) during the breeding season, which may be an adaptive response for
226 any fast-living species with a short lifespan. The authors suggested that life-history
227 traits are stronger predictors of short-term physiological responses to disturbances
228 than population status. Such new generations of sensors will notably help to refine
229 concepts that will serve as the basis for future models of environmental justice,
230 guaranteeing the right for everyone to live in a healthy, balanced and health-friendly
231 environment, while taking part in its preservation.

232 In every ecosystem, organisms live in interaction with others through trophic
233 activities, exchange of molecules, communications, competition for common
234 substrates or habitats, and such interactions may inspire innovative applications as
235 illustrated in the following section.

236

237 **Applications based on organism interactions**

238

239 In natural ecosystems, some organisms can be more opportunistic than
240 others, but all organisms contribute to the ecosystem, as well as to its functioning
241 and sustainability. Complementarity of habitats and functions amongst organisms
242 which live in the same ecosystem leads to the concept of multifunctionality of an
243 ecosystem, when combinations of species can simultaneously perform more
244 functions and at higher levels, than species can individually. This has been illustrated
245 by an experimental study (Godwin et al 2018), showing that the number of algal
246 species in an intensive algal polyculture enhanced the number of functions at higher
247 levels (e.g. stability, resistance to invasion) than could any of the algal monocultures.
248 The authors concluded that while an algal monoculture may be the optimal choice for
249 maximizing short-term biomass production, algal polycultures could offer a more
250 stable crop of the desired species over longer time periods. Similarly, Pessiot et al
251 (2012) provided evidence that complex and diversified microbial communities offer
252 considerable advantages in degrading complex organic waste in order to produce

253 biomolecules of biotechnological interest. **(BOX 2)** Additionally, rarely abundant
254 species may play an important role in communities. Sierocinski et al (2018)
255 evidenced a positive relationship between methane production and the richness of
256 the observed species, with little evidence of functional saturation, suggesting that
257 rare species play an important role in methane-producing communities. Therefore,
258 the resilience of methanogenic communities in an anaerobic digester, used to treat
259 waste, will depend on the initial composition, which requires inoculating multiple
260 communities.

261 **BOX 2:** AFYREN is founded in 2012 and is a company developing and using
262 microbial innovative assemblages for the transformation of agro-industrial by-
263 products into 100% bio-based products. These natural organic acids and their
264 derivatives are efficient solutions to produce food and animal feed, flavours and
265 fragrances, lubricants, materials science and life sciences. This production is carried
266 out thanks to its innovative technology, low carbon and zero waste, based on natural
267 microorganisms and patented throughout the world, through 10 families of patents,
268 and is the result of more than 10 years of R&D. It is an "all-in-one" non-GMO
269 fermentation technology that can be transposed to a global scale. <https://afyren.com/>



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271 © Afyren
272

273 Close interactions may also occur between very different organisms. This is
274 the case, for instance, for the well-known example of symbiosis occurring in corals,
275 where an animal provides a specific habitat for the algae that produce sugars from
276 photosynthesis which are, in turn, useful to the animal. Such positive interactions
277 between organisms (*i.e.* facilitation) may be used to increase the resilience and
278 growth of whole communities. For example, Silliman et al (2015) reported that
279 placing propagules next to, rather than at a distance from, each other, for wetland
280 restoration purposes, lowered anoxia and decreased edge erosion stress, leading to
281 increased density and aboveground biomass by more than 100%, on average. This
282 study highlights the use of ecological facilitation theory in restoration designs, used
283 with the aim of enhancing conservation efforts.

284 What is more, microorganisms living closely to macro-organisms, such as
285 bacteria living in soil close to plant roots, may constitute a source of information on
286 neighbourhood or even host health. In a very recent study, Zolti et al (2020) reported
287 that the genetic potential (DNA) and the gene expression patterns (RNA) of plant-
288 associated microbial communities can reveal specific stress signals, related to the
289 experimentally changing environmental conditions, that were not observed during the
290 transcriptional profiling of host plants on their own. The authors suggested that
291 microbial profiling could be used as an early microsensor for evaluating *in situ*
292 conditions experienced by host organisms, and that these could be applied to a wide
293 range of host systems.

294 Interactions between organisms involving trophic and recycling activities, as
295 classically observed in nature, may also be sources of inspiration for a more
296 sustainable way of producing food, such as permaculture, agroforestry or organic
297 agriculture. Similar ecological concepts can also be applied to marine aquaculture
298 systems, where one farmed species can provide a source of food for another
299 species. Li et al (2019) demonstrated that microalgae can grow using fish waste, and
300 oysters can eat algae to produce good-quality, healthy food, reducing the waste
301 generated by aquaculture farms.

302 The behaviour and growth of organisms are strongly dependent on their living
303 environment, which may, in turn, be modified by these organisms. Such interactions
304 could be used to propose innovative ways for managing natural or anthropized
305 ecosystems, as illustrated in the following section.

306

307 **Applications based on organism-environment interactions**

308

309 Animals, plants and microorganisms are not only influenced by their
310 environment, they are also known to strongly influence their surrounding environment
311 themselves, as well as its properties. Some organisms are used as eco-technical
312 processors for the restoration or the ecological management of land, rivers, lakes,
313 oceans and cities. For example, beavers have well known effects on
314 hydromorphology through dam construction. Law et al (2017) reported that the
315 introduction of beavers in agriculturally-degraded fens increased light penetration
316 (through direct removal or flooding-induced recession of the tree canopy or taller
317 understory herbs) and elevated soil moisture (from dam creation). The combined
318 effect of grazing and waterlogging by beavers increased plant diversity and
319 heterogeneity after 12 years of presence. This illustrates a passive but innovative
320 action to face the problems of wetland habitat degradation.

321 Regarding exploited ecosystems, providing a description and understanding of
322 the functioning of such agricultural ecosystems (i.e. agro-ecosystems) make it
323 possible, for example, to propose alternative solutions to the use of chemicals for
324 rodent control. Ecological findings, such as the use by common voles of tunnel
325 networks dug by moles, as well as tall grass, as refuges from red foxes and birds of
326 prey, can be used to reduce common vole densities by destroying such refuges, and
327 thus avoiding the use of poisoned rodent bait in agro-ecosystems (Coeurdassier et al
328 2014). Such an ecological approach to rodent control could help resolving
329 conservation and agriculture issues. Innovative approaches and implementations of
330 bio-indicators for environment management are also proposed. Studies concerning
331 the relationships between soil physico-chemical properties and biological
332 assemblages, that may considerably influence the functioning of the system through
333 synergies or antagonisms, have led to the identification of three main soil functions
334 (i.e. carbon transformation, nutrient cycling and structure maintenance). Indicators,
335 based on variables related to those three core functions, were then proposed by
336 Thourmazeau et al (2019) in order to provide a direct assessment of soil quality.
337 These can then be used for managing cropping systems or capacity building by local
338 stakeholders (**BOX 3**).

339

340 **BOX 3:** Biofunctool® is an in-field 357 Consulting Services) in France and
341 package to assess the impact of 358 abroad.

342 agricultural practice on soil functioning. 359 <https://www.biofunctool.com/>

343 Biofunctool® indicators evaluate in situ
344 the quality of soil through the
345 measuring of the functions driven by
346 soil biotic activities (respiration, nutrient
347 cycling, carbon sequestration, soil
348 structure). These tools are meant to be
349 financially accessible and easy-to-use,
350 not requiring a high level of expertise.
351 Biofunctool® helps to promote
352 agroecological practices and arouses
353 growing interest from many users
354 (Research and Technical Institutes,
355 Public agricultural organisations, 360
356 NGOs, Environnemental Engineering 361



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362

363 Regarding wildlife within urban ecosystems, large-scale ecological networks
364 are important for the conservation of species, since insuring landscape connectivity
365 will allow individuals to move and exchange genes, thereby ensuring the survival of
366 populations. Tarabon et al (2020) used a habitat network connectivity model based
367 on landscape graphs in order to estimate the impacts of projected urban dynamics on
368 the habitat of species in an ecologically relevant way. They demonstrated that the
369 most highly impacted animal species by the future urban sprawl of a large city were
370 those associated with open and semi-open areas and cultivated plots. Such an
371 original approach can improve the application of the mitigation hierarchy (avoiding,
372 reducing and compensating for the impacts on biodiversity), especially by anticipating
373 future land and conservation conflict areas. Using an experimental approach, Balbi et
374 al (2019) followed the individual movement patterns of trans-located and radio-
375 tracked hedgehogs (*Erinaceus europaeus*) in the city of Rennes (France). They
376 observed that individuals travelled longer distances, moved faster, and were more
377 active in highly connected contexts, as opposed to disconnected ones. The authors
378 thus validated the ecological relevance of modelling analysis, which identifies routes

379 between habitat patches that minimize the cumulative resistance to movement (i.e.,
380 the cost of movement), and correspond to paths of higher movement probability. In
381 this way, such an analysis identifies highly connecting areas, and could now be
382 easily implemented by urban landscape planners.

383 Despite the increasing human needs for growth and welfare, a better
384 integration of nature in everyday human life is possible for the benefit of all, as
385 illustrated in the following section.

386

387 **Applications based on socio-ecosystems**

388

389 Understanding the origin and the consequences of environmental changes
390 requires a review of ecological processes while considering their links with social
391 processes. The concept of socio-ecological systems (SESs) is now widely used to
392 describe the relationship between social, economic, cultural, political, and ecological
393 functions, as well as their temporal co-evolutions. Observing and modelling SESs led
394 to several innovations, which intend to provide combined services to “un-disturb”
395 SESs by restoring their ecological functions, and even compensating for ecological
396 disturbances.

397 Global Ecology and interdisciplinary studies thus paved the road towards
398 strategies offering mutual benefits to biodiversity and to people. Chazdon et al.
399 (2020) showed how the development of riparian corridors, connecting forest
400 fragments in the Pontal do Paranapanema region of São Paulo State (Brazil), over
401 the course of 35 years and tended by local farming families, allowed the latter to
402 benefit from the intermingled trees, wildlife and crops. Indeed, the reforested
403 corridors facilitated the movement of endangered wildlife between core zones of the
404 forest, and further played a role in carbon neutralization and storage in the Pontal
405 region. Local people, who were involved in this trajectory, gained income, food
406 security and knowledge, as well as a growing sense of concern for ownership and
407 collective responsibility towards wildlife and forest conservation.

408 Nature reintroduction within cities also directly profits wildlife and the
409 conservation of threatened species. The ecological and physical functions of urban
410 green spaces also take part in various other services which benefit the human
411 population, such as social capital, soil infiltration, reduction of pesticide needs,
412 carbon sequestration, and awareness of nature preservation. For example, Mavoia et

413 al (2019) investigated the relationships between greenness (satellite data),
414 biodiversity (fauna and flora inventories), and blue space (water areas), with the
415 subjective wellbeing of people living in metropolitan Melbourne (Australia). They
416 evidenced that subjective wellbeing was associated with greenness (overall, private
417 and public) and biodiversity, and highlighted the significance of the association
418 between private greenness and subjective wellbeing.

419 Faced with the high heterogeneity of urbanized areas and the complexity of
420 interactions, modelling tools are still being developed to better consider the
421 interactions between buildings, vegetation, atmosphere and solar energy. These
422 tools provide new insights that can help urban designers to work with nature, whilst
423 taking into consideration climate, vegetation, biodiversity, topography, as well as
424 human behaviours and needs (bioclimatic concept). Using such a digital tool, in
425 addition to onsite measurements, Hsieh et al. (2016) demonstrated that wind speed
426 and shading both influenced human comfort. Indeed, these authors showed that
427 excessive planted trees in an urban subtropical area, without considering wind
428 corridors, can affect urban ventilation and thus reduce their cooling effect. .

429 Construction is becoming a source of innovations, arising in order to control
430 and reduce all kinds of fluxes (energy, waste, water, air pollution, etc.). The
431 integration of domesticated microorganisms in human everyday life, through waste
432 recycling or energy consumption reduction, is also a consideration. Given the
433 propensity of microalgae to capture light spectrum energy and release thermal
434 energy, the SymBIO2 consortium, headed by XTU, through Pruvost et al studies
435 (2016), showed that, in summer, microalgae cultivation in thin vertical reactors
436 embedded in building walls can filter sun light and reduce the thermal load on the
437 building, while in winter, excess thermal energy in the cultivation system can be used
438 to warm the building (**BOX 4**).

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447 **BOX 4:** XTU is an award-winning architecture, ecological innovations and design firm
448 founded in 2000. Located in Paris, France, XTU specializes primarily in academic
449 and environmental research in addition to residential and cultural buildings. XTU
450 engages its innovative research on the themes of bio-inspired and photosynthetic
451 architecture. In addition to these innovations, XTU also develops biofacades
452 (EP2734681A2, 2009 and EP2367926B1, 2011) for cultivating plankton species on
453 the exteriors of buildings and creating new architectural ecosystems. A first
454 microalgae-producing biofacade will be settled onto the AlgoHouse building in Paris
455 in the following years. <https://www.xtuarchitects.com/>



456
457 © XTU

458
459 Using a metabolic approach, conceptualizing constructions as organisms
460 which require goods and energy to maintain functionality and support growth, while
461 emitting waste as a by-product, Yi (2018) qualified the performance of a building.

462 Indeed, the author demonstrated that human behaviour is a main determinant of
463 building sustainability. Goldstein et al. (2013) applied such metabolism concepts,
464 along with a life cycle assessment (LCA) approach, and on the scale of a city, in
465 order to assess the environmental impacts of five cities along their supply chain and
466 life cycles. These authors suggested that the richest cities may mainly reduce their
467 environmental impacts by reducing personal consumption, while the poorest ones
468 should pay more attention to infrastructure improvement. Such studies help to
469 identify the processes that need to be improved in order to make the entire supply
470 chain more sustainable.

471 Recycling, managing waste, promoting short lines of supply with social
472 insertion and sharing (products, buildings, experiences & information) are all
473 practices that modern society is (re)discovering. Boyer et al. (2014) highlighted an
474 example of social innovations, based on community initiatives and consensus
475 decisions made by cohoused inhabitants in an Eco Village, in the Town of Ithaca,
476 New York. These authors reported low-impact lifestyles and measurably lower
477 ecological footprints with non-profit management, with no sacrifice to quality of life,
478 through the use of common open spaces, community-supported farms, and
479 independent businesses with a net-zero energy budget (the consumers produce as
480 much energy as they consume).

481 A step further in the SES research process remains to be taken, which needs
482 to involve stakeholders and local populations in order to foster research, as well as
483 the transfer of knowledge and expertise. Indeed, this approach has been applied in a
484 Natura 2000 site (Dupont et al 2016). Stakeholders were first involved in the co-
485 construction of a conceptual model, based on vegetation dynamics and human
486 actions (tourist traffic, conservation and agricultural actions). The study suggests that
487 maintaining actions initiated during the implementation of Natura 2000, would also
488 maintain the richness of species, as well as the presence of rare species within plant
489 communities. However, multiplying conservation actions, characterised by a
490 reduction of closed surface areas and an increase in open areas, would have the
491 opposite effect on rare species in different communities.

492 Studies concerning human and nature interactions, constituting socio-
493 ecosystems, not only provide new concepts or solutions for a more sustainable living
494 environment; they also help to increase their environmental and social acceptability.

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500 **Conclusion**

501 As illustrated above, research in Ecology and Environment may not only
502 provide knowledge on the functioning and threats to ecosystems, it also proposes
503 market-based technological, as well as social, innovative solutions to ensure both
504 nature conservation and human needs and welfare. This is made possible through
505 the stronger integration of human issues within ecological and environmental studies
506 and the urgent demand of humans for a more sustainable living environment

507 For example, the « One World, One Health » concept is a recent one, based
508 upon the existing relations between human health, animal health and environment. A
509 large proportion of infectious diseases are zoonotic diseases, and their impact on
510 human health might greatly affect societies, as well as the economy, as the covid-19
511 pandemic has sadly evidenced. Research in eco-epidemiology, using the “One
512 Health” approach, highlighted the significance of ecological management
513 opportunities as a possible lever to improve healthcare and limit public health
514 hazards.

515 Regarding the increasing societal and industrial demand for nature-inspired
516 innovations, the biomimicry approach is an opportunity for research to introduce
517 more environmental ethics, by proposing ecologically- and environmentally-aware
518 innovations, such as the use of degradable materials, reducing the use of natural
519 resources or producing less waste, for instance.

520 The development of information technology and the increasing public
521 awareness of environmental issues allow citizen science to gain larger audiences of
522 volunteers willing to engage in scientific studies. The number of observations, the
523 scale of resolutions, and the access to local knowledge can therefore be multiplied.
524 In return, citizen science contributes to lifelong science education and increases the
525 public’s understanding of science.

526 The transfer of ecological and environmental knowledge, concepts and
527 innovations, to society as a whole is crucial in research, in order to foster
528 relationships with stakeholders, as well as industry, but also to gain social
529 acceptance and to enlighten political decisions.

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536 REFERENCES

537

538 Balbi M, Petit EJ, Croci S, Nabucet J, Georges R, Madec L, Ernoult A (2019)
539 Ecological relevance of least cost path analysis: An easy implementation method for
540 landscape urban planning. *Journal of Environmental Management*, 244: 61-68.

541

542 Bisson I-A, Butler LK, Hayden TJ, Kelley P, Adelman JS, Romero LM, Wikelski MC
543 (2011) Energetic response to human disturbance in an endangered songbird. *Animal
544 Conservation* 14: 484-491

545

546 Bourret V, Gamble A, Tomos J, Jaeger A, Delord K, Barbraud C, Totosa P, Kada S,
547 Thiebot J-B, Thibault E, Gantelet H, Weimerskirch H, Garnier R, Boulinier T (2018)
548 Vaccination protects endangered albatross chicks against avian cholera.
549 *Conservation Letters* 11: e12443.

550

551 Boyer R (2014) Sociotechnical Transitions and Urban Planning: A Case Study of
552 Eco-Cohousing in Tompkins County, New York. *Journal of Planning Education and
553 Research* 34: 451-464.

554

555 Chazdon RL, Cullen L, Padua SM, Padua CV (2020) People, primates and predators
556 in the Pontal: from endangered species conservation to forest and landscape
557 restoration in Brazil’s Atlantic Forest. *R Soc open sci* 7:200939.

558

559 Coeurdassier M, Riols R, Decors A, Mionnet A, david F, Quintaine T, Truchetet D,
560 Scheifler R, Giraudoux P (2014) Unintentional Wildlife Poisoning and Proposals for
561 Sustainable Management of Rodents. *Conservation Biology*, 28: 315-321.

562

563 Dupeyroux J, Viollet S, Serres JR (2019) An ant-inspired celestial compass applied
564 to autonomous outdoor robot navigation. *Robotics & Autonomous Systems*, 117: 40-
565 56.

566

567 Dupont H, Gourmelon F, Rouan M, Le Viol I, Kerbiriou C (2016) The contribution of
568 agent-based simulations to conservation management on a Natura 2000 site. *Journal*
569 *of Environmental Management*, 168: 27-35.

570

571 Godwin CM, Lashaway AR, Hietala DC, Savage PE, Cardinal BJ (2018). Biodiversity
572 improves the ecological design of sustainable biofuel systems. *Global Change*
573 *Biology Bioenergy*, 10: 752-765.

574

575 Goldstein B, Birkved M, Quitzau M-B, Hauschild M (2013) Quantification of urban
576 metabolism through coupling with the life cycle assessment framework: concept
577 development and case study. *Environ. Res. Let.* 8: 035024.

578

579 Hunt RJ, Borchardt MA, Bradbury KR (2014) Viruses as groundwater tracers: using
580 ecohydrology to characterize short travel times in aquifers. *Ground Water*, 52:187-93.

581

582 Hsieh CM, Jan FC, Zhang L (2016) A simplified assessment of how tree allocation,
583 wind environment, and shading affect human comfort, *Urban Forest & Urban*
584 *Greening*, 18, pp. 126-137, 186.

585

586

587 Law A, Gaywood J, Jones KC, Ramsay P, Willby NJ (2017) Using ecosystem
588 engineers as tools in habitat restoration and rewilding: beaver and wetlands. *Science*
589 *of the Total Environment*, 605-606:1021-1030.

590

591 Lee ES, Kim D, Youn YS, Oh KT, Bae YH (2008) A virus-mimetic nanogel vehicle.
592 *Angew. Chem. Int. Ed.* 47, 2418–2421.

593

594 Li M, Callier M, Blancheton J-P, Galès A, Nahon S, Triplet S, Thibault G, Menniti C,
595 Fouilland E, D'Orbcastel E (2019) Bioremediation of fishpond effluent and production

596 of microalgae for an oyster farm in an innovative recirculating integrated multi-trophic
597 aquaculture system. *Aquaculture*, 504: 314-325.

598

599 Mavoia S, Davern M, Breed M, Hahs A (2019) Higher levels of greenness and
600 biodiversity associate with greater subjective wellbeing in adults living in Melbourne,
601 Australia. *Health & Place* 57:321–329.

602

603 Melo N, Wolff GH, Costa-da-silva AL, Arribas R, Fernandez Triana M, Gugger M,
604 Riffell JA, DeGennaro M, Stensmyr MC (2020) Geosmin attracts *Aedes aegypti*
605 mosquitoes to oviposition sites. *Current Biology*, 30: 127-134.

606

607 Moffat AD, Elliston A, Patron NJ, Truman AW, Carrasco Lopez JA (2021) A
608 biofoundry workflow for the identification of genetic determinants of microbial growth
609 inhibition. *Synthetic Biology*, 6: ysab004.

610

611 Neethling E, Petitjean T, Quérol H, Barbeau G (2017) Assessing local climate
612 vulnerability and winegrowers' adaptive processes in the context of climate change.
613 *Mitigation and Adaptation Strategies for Global Change*, 22:777–803.

614

615 Pessiot J, Nouaille R, Jobard M, Singhanian RR, Bournilhas A, Christophe G,
616 Fontanille P, Peyret P, Fonty G, Larroche C (2012). Fed-batch anaerobic valorization
617 of slaughterhouse by-products with mesophilic microbial consortia without methane
618 production. *Appl Biochem Biotechnol*, 167, 1728–43.

619

620 Pruvost J, Le Gouic B, Lepine O, Legrand J, Le Borgne F (2016) Microalgae culture
621 in building-integrated photobioreactors: Biomass production modelling and energetic
622 analysis. *Chemical Engineering Journal*, 284: 850-861.

623

624 Rousselot M, Delpy E, Drieu La Rochelle C, Lagente V, Pirow R, rees J-F, Hagege
625 A, Le Guen D, Hourdez S, Zal F (2006) *Arenicola marina* extracellular hemoglobin: a
626 new promising blood substitute. *Biotechn J.1*: 333-45.

627

628 Sierocinski P, Bayer F, Yvon-Durocher G, Burdon M, Grobkopf T, Alston M,
629 Swarbreck D, Hobbs PJ, Soyer OS, Buckling A (2018). Biodiversity–function
630 relationships in methanogenic communities. *Molecular Ecology*, 27: 4641-4651.
631

632 Silliman BE, Schrack E, He Q, Cope R, Santoni A, van der Heide T, Jacobi R, Jacobi
633 M, van de Koppel J (2015) Facilitation shifts paradigms and can amplify coastal
634 restoration efforts. *PNAS*, 112:14295-14300.
635

636 Tarabon S, Calver C, Delbar V, Dutoit T, Isselin-Nondedeu F (2020) Integrating a
637 landscape connectivity approach into mitigation hierarchy planning by anticipating
638 urban dynamics. *Landscape and Urban Planning*, 202: 103871.
639

640 Thourmazeau A, Bessou C, Renevier M-S, Panklang P, Puttaso P, Peerawat M;
641 Heepngoen P, Polwong P, Koonklang N, Sdoodee S, Chantuma P, Lawongsa P,
642 Nimkingra P, Thaler P, Gay F, Brauman A (2019) Biofunctool®: a new framework to
643 assess the impact of land management on soil quality. Part A: concept and validation
644 of the set of indicators. *Ecological Indicators*, 19: 100-110.
645

646 Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, Toyohara K,
647 Miyamoto K, Kimura Y, Oda K (2016) A bacterium that degrades and assimilates
648 poly(ethylene terephthalate). *Science*, 351: 1196-1199.
649

650 Zhang J, Liu L, ren Y, Chen F (2019) Characterization of exopolysaccharides
651 produced by microalgae with antitumor activity on human colon cancer cells.
652 *International Journal of Biological Macromolecule*, 128: 761-767.
653

654 Zolti A, Green SJ, Sela N, Hadar Y, Minz D (2020) The microbiome as a biosensor:
655 functional profiles elucidate hidden stress in hosts. *Microbiome*, 8: 71.
656