How improving genetic technologies have advanced the field of ecology

ABSTRACT

Within biology, there are two main fields that attempt to determine why living species and organisms are the way that they are: genetics and ecology. Genetics is the study of gene theory and heredity, and ecology is the study of organisms' interactions with other organisms and their natural surroundings, with a large focus on evolution. Both the fields of genetics and ecology have advanced rapidly over the past 200 years since their founding principles were proposed. Genetics has become more advanced due to geneticists creating and perfecting new technologies to look at and understand the submicroscopic elements of genes in DNA. This is also why the field of ecology has been advancing. Ecologists began looking at organisms as a whole to determine their history of speciation, evolution and different mannerisms. But now, genetic technologies have allowed ecologists to look at and read genes and DNA sequences to come to more accurate conclusions. This review will look at the history of the fields of genetics and ecology and how specifically advancements in the field of ecology have followed major advancements in technology or ideologies in the field of genetics.

INTRODUCTION

Within biology–the study of life–there are many different ideas as to why living organisms function the way that they do. Mainly, there are the four founding principles of biology–cell theory, the theory of evolution, gene theory, and homeostasis–that help to explain life as we know it. These principles are the main ideas that are studied today and help drive the field biology forward. The concepts behind each of these principles are different, but there is heavy overlap as they all are explaining the overarching idea of sustaining life on Earth. As "life" and biology are very broad, they are studied in many different specialized fields. Two of those main fields of study in biology are genetics and ecology. Genetics is the study of gene theory and heredity, and ecology is the study of organisms' interactions with other organisms and their natural surroundings (Wilkin and Gray-Wilson 2016).

Genes–and gene theory–in genetics are how different traits are encoded in an organism's DNA and expressed outwardly, while heredity is how those traits are passed on from parent to offspring throughout generations (Pierce 2020). This is important because this means that the field of genetics works on a submicroscopic level to explain things visible to the human eye. Alternately, ecology studies how organisms and populations of organisms are impacted by their surroundings on a macroscopic level. Within ecology, there is also the main idea of evolution which is how species of organisms have developed and diverged into different species over time (Wilkin and Gray-Wilson 2016). Evolution happens gradually–slower than can be visualized within one lifetime–and it is due to the ecological impacts on different organisms and the heredity of traits between generations (Darwin 1882). This ecological concept is where the two major fields intersect.

Because evolution is the founding principle of the ecology field, and genetics play such a big part in determining how evolution can occur, many major advancements in the field of ecology are only able to occur because of advancements that are made in the study of genetics. Specifically, as genetic technologies have advanced, ecologists have been able to better visualize and understand the submicroscopic causes of evolution and therefore understand more advanced ecological concepts that couldn't be seen before. This phenomenon can be seen throughout the last almost 200 years as both fields have rapidly been advancing with new technologies and studies. This historical review will look from the founding principles of each field being discovered to how different technologies in each field are being used in current studies.

FOUNDING PRINCIPLES OF ECOLOGY AND GENETICS

Both the fields of genetics and ecology were built on one of the founding principles of biology. Genetics studies genes and gene theory while ecology looks at evolution and natural interactions. Both fields can be traced back to the specific studies that are credited with discovering their respective founding principles. In genetics, Gregor Mendel famously outlined simple gene theory by looking at heredity in pea plants (Mendel 1865). And in ecology, Charles Darwin discovered and detailed the tenets of natural selection and evolution (Figure 1) by studying different species of finches in the Galapagos Islands (Darwin 1882).

These studies led to the main discoveries of their respective fields, but it took a while for the findings to be accepted by the scientific community; specifically, the theory of evolution took a long time to be accepted after Darwin detailed his findings, because it was impossible to visualize and think that populations of species could change based on interactions with nature and other species around them. Because the evolutionary changes in species happen so slowly, no one person–except for scientists studying organisms with very short lifespans–can see evolution occur in their lifetime, so it was an abstract idea for a general audience to understand in a field that relied so heavily on physical information.

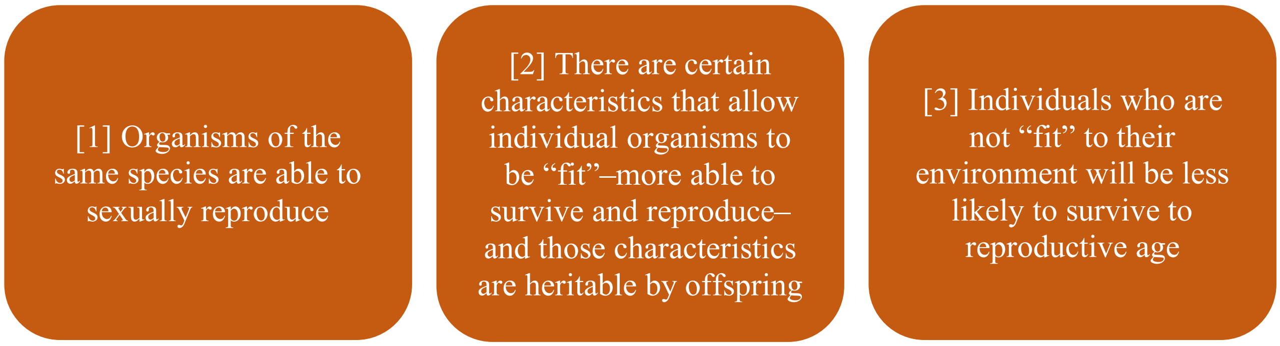

Figure 1: The three main tenets of evolution as outlined by Darwin's theory (Pearson 1910).

Conflicting Opinions on Evolution.

After Darwin detailed his theory of evolution, he was flooded with critiques of how evolution didn't make sense or couldn't be possible. These critiques, however, mainly focused on disproving or discrediting small points of Darwin's theory in an attempt to disprove the whole theory. Pearson (1910) wrote a review using early 20th century research– "current" research at the time–to disprove the theory of evolution. His main arguments were that many studies he reviewed did not find fertility to be heritable, meaning that mothers and daughters of different species would reproduce differently, whether that be one had more children than the other, they had different clutch sizes, or they produced offspring at different stages in life. To Pearson, the differences in fertility seemed to prove that fertility itself was not a heritable trait, making one of Darwin's tenets unlikely (Figure 1.2), and therefore the whole theory improbable.

Many other opposers of evolution advocated for the Special Creation Theory from the bible, which states that God created all of the creatures of the land and sea and then man and woman in his image (Lawson 1999). This theory directly conflicts with the idea of evolution, as it states that all creatures were created as they were while evolution states that they evolved from different organisms over time. Many individuals at the time already held belief that God created all of the creatures on Earth, so a new, conflicting idea was hard to comprehend (Masci 2019). Finally, other theistic believers even admit that Darwin could be right that evolution could occur in theory, but that the Earth simply wasn't old enough for all the diversity we see in living organisms to have evolved, meaning that there had to be something else driving the species diversity present (Singham 2021).

Some of the biggest advocates for evolution were zoologists and botanists who had already seen similar species of plants or animals and found that Darwin's ideas helped explain how the species were so similar in many ways but still different (Evolution in…1877). Other advocates for the theory were scientists whose specialties branched toward the genetics field. One of the best arguments for evolution–and the eventual reason the theory was accepted–after Darwin proposed it was that heritability would cause "better" traits–or traits that made an organism more fit to their environment–to become more prominent over time (Romanes 1895; AAAS 1899). This meant that if there were a trait that was undesirable, it could cause specific organisms of a species to go die early and that trait to be eliminated by natural selection (Figure 1.3). Many of the first people who believed in Darwin's theory of evolution did so because they believed in Mendel's theory first. The background in genetics took Darwin's macroscopic concept and explained it on the molecular level which made the theory more believable for these scientists.

EARLY RESEARCH IN ECOLOGY

There were many large research studies done in the late19th/early 20th centuries that came to conclusions that could have more easily been found with genetic technologies today. There were many large studies to determine the relationship between known species of organisms, or if similar organisms in a population were the same species with varied expressed traits, or different species altogether. One of these studies by Theodore Gill (1873) was performed using paleontological data. Gill compared bones of different whale species to not only determine if the whales were different species, but to decide if whales were more closely related to mammals or fish. Data in his study only consisted of evidence that could be seen with the human eye, as that is all he was able to use. Other studies on speciation used organ size (Dodds and Hisaw 1924a), different movement patterns (Dodds and Hisaw 1924b, 1925), structure (Forsaith 1920), or even habitat (Dodds and Hisaw 1925) to determine if organisms were different species or not. Some similar studies even felt the need to explicitly state that the findings in the paper were just observations and may need to be "modified or discarded altogether" based on new findings (Whitford 1901).

Because the early research being done in the ecology field was based on such subjective data and information, it was hard to come to one conclusion on any topic that had enough evidence for every scientist to accept it as true. Speciation was a big subject of study in ecology at the time, but without DNA testing, there was no precise way for scientists to tell how related certain organisms were or not. This means that conclusions drawn in one study may have been rejected in another based on what data type of was collected and how it was analyzed.

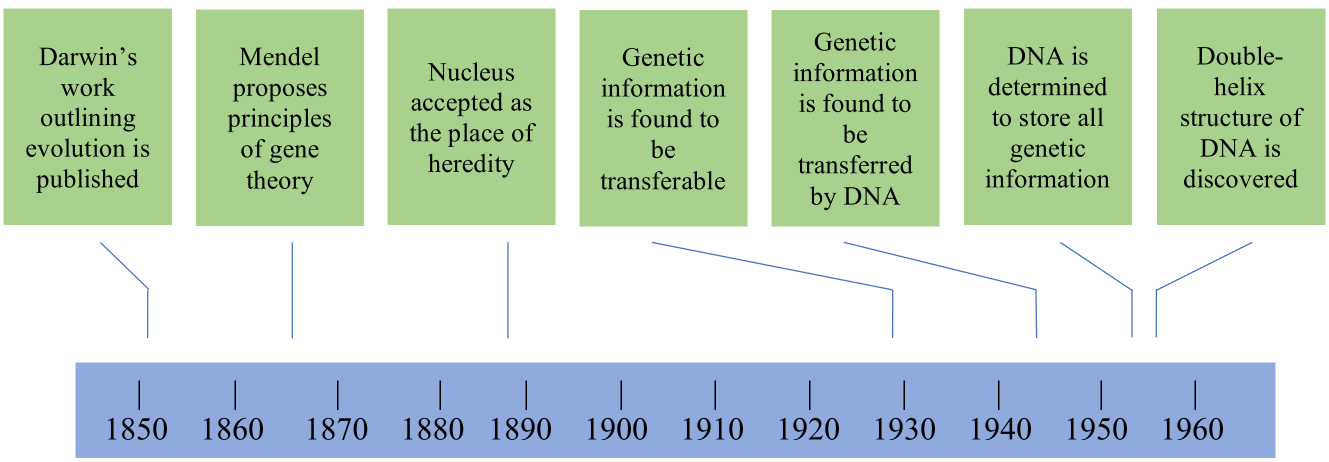

Figure 2: A timeline of the major genetic discoveries from 1850 to 1954 (figure adapted from Pierce 2020).

EVOLVING GENETIC TECHNOLOGIES

From the late 19th to mid-20th centuries, major advancements were being made in the field of genetics with regards to the function and structure of DNA (Figure 2). Most of these advancements built off the experiments that came before them to slowly build an understanding of how DNA functions in living organisms to store genetic information. By the mid-1950s, the role of DNA as storage for genes was very well studied (Pierce 2020). There was still a lot of work to be done in studying genes and gene expression, but the basic function of genes as established in Mendel's gene theory were accepted and used practically in the genetics field. This also meant that other fields such as ecology could start implementing new ways to analyze their own data using genetics. In the mid-to-late 1900s there are many studies conducted in the ecology field that do just that.

Evolving Genetic Technologies in Ecology

Speciation studies in the later 1900s were performed very differently than the ones done before this time. There were many studies to determine how population size affects the speed and degree of speciation, specifically in small populations (Nei et al. 1975; Templeton 1981; Ellstrand and Elam 1993; Coyne and Orr 1998). These studies would use genotypes collected based off of phenotypic presentation of different organisms. One specific study that used more advanced techniques–by Alan R. Templeton (1981)–used population genetics to determine what happens to different individuals and populations during periods of isolation that lead to speciation. To collect genotypic data, he analyzed karyotypes and DNA sequences to find homologous elements between isolated organisms to determine their evolutionary proximity. The depth of the DNA sequences, however, was nowhere near as detailed as they are today, so the sequencing data collected was still supported with physical/non-genetic traits to properly analyze the species' relationships.

Other studies on speciation at the time were using genetics to describe the definite boundaries between species. Nei et al. (1975) used a mathematical way to determine genotype ratios in a small population. They used physical–i.e. not genetic–evidence to determine phenotypes and proposed equations to estimate genotypic ratios. This is also not an exact method, but was an attempt to seriously implement genetic ideas in ecology studies.

A speciation study by Coyne and Orr (1998) proposed that there wasn't enough overlap between studies in evolution and genetics. They suggested that evolutionary and speciation studies using genetic evidence would yield more convincing results. They demonstrated this in their own study by using genetics to more accurately depict the relatedness of *Drosophilia* species. Studying the *Drosophilia* also allowed Coyne and Orr to compare the evolutionary path they found to other known species. Because their findings were rooted in DNA and genetics–which is universal between all species–they were able to accurately compare the evolutionary pathway to any other organism studied where the data was also collected with genetics. Genetics in this type of ecological research allows for a common ground for comparison between results. This commonality in research was allowing ecological studies to build off one another to further information in the field.

CURRENT USE OF GENETICS TECHNOLOGIES IN ECOLOGY

Current research the field of ecology relies heavily on genetic technologies. As techniques such as sequencing and analysis of genomes have become more common and less expensive, ecological studies looking at relatively small species like insects or fish have the capabilities to sequence large numbers of organisms very quickly (Kwon et al. 2022; Sherpa et al. 2022). Studies like that of Kwon et al. (2022) and Sherpa et al. (2022) are very similar to the ones that were done in the late 1900s, just with more advanced genetic technologies. These new technologies include Next Generation Sequencing techniques that allow butterflies or betta fish to be entirely sequenced relatively quickly and easily for relatively inexpensive. These experiments build on the ones before them by using the accurate genotype of every individual studied by looking straight in the genes. The equational ratios discovered to convert phenotypes to genotypes were helpful when studying populations, but not as accurate as coding the genes in the DNA.

Newer studies also have new goals. Studies looking at genotypes in the past did so to determine how speciation occurred and the evolutionary history different organisms. Current studies, however, can go further. A study by Kwon et al. (2022) looked to determine the evolutionary history of domesticated betta fish, but their goal was to assay using genetics as a way to determine exactly how and approximately when species differentiated. Using the data collected from the betta fish, the researchers were able to determine that betta fish domestication began approximately 700 generations ago as well as being able to determine that specific changes in color, fin shape and sex determination occurred via genetic hybridization. The methods they used on this study are going to be used in future studies on other species to more precisely understand evolutionary history better than we could have only 20 years ago.

A more significant focus in the ecology field is also conservation. Many researchers are working to conserve different plant and animal species by many different methods. This relates to genetics because one of the greatest harms to small populations of species is low genetic diversity. Many studies are able to accurately determine gene frequencies by Next Generation Sequencing and determine the best course of action for conservation. One example of this is a study of different populations of Scarce Heath butterflies by Sherpa et al. (2022). They sequenced 100 different butterfly to determine the genotypes at over 817 different loci and found that 2 of the three populations they looked at had relatively healthy gene pools, but the third population was the smallest with the least genetic diversity, so they recommended conservation of just the one population that needed it.

Overuse of Genetic Technologies

Genetic technologies have become so common that they're used in almost every crop food grown today (Kuzma and Greigor 2020). Genetically Modified Organisms, or GMOs, are made by inserting desired genes from one organism into another. Usually to increase marketability, taste, or shelf life in crops. Kuzma and Greigor published a review in 2020 detailing how GMOs have become so common that ecologists are now studying the impact of GMOs on wildtype (non-genetically modified) organisms–specifically other plants. GMOs accidentally pollinating wildtype plants can change the gene pool irreversibly. Because the research on GMOs has gone so far, the United States Department of Agriculture has implemented laws to regulate the use of GMOs to lessen the effects on the surrounding wild environments. These laws are required to be followed by all farmers to help keep the natural environment safe. They are only in place, however, because of how commonplace genetically modifying organisms have become.

Separately, genetic technologies have been used–and possibly overused–in many positive ways. Because of the vast research in the ecological fields using genetic technologies, there are databases storing the genomic sequences of almost every organism (NCBI 2022). These databases allow for searches to be done using unknown DNA that match it to the most similar known species' DNA. Because of this, researchers like Silva et al. (2020) are coming up with new ways to collect and amplify large amounts of DNA so that they can be analyzed and many species can be identified at once. Technologies like these are important because small samples of an organism can be studied and identified using only genetics. This will allow ecologists to determine what species are in certain areas using just found DNA samples.

FUTURE EXPERIMENTS

The field of genetics is currently changing which means that the ecology field will almost certainly be right behind. There is a lot of controversy over new technologies being created and perfected now that can edit genes in someone's genome. One of the most common of these gene editing technologies is the CRISPR gene editor. This technology essentially allows for scientists to change genes at the nucleotide level to express desired traits (Pennisi 2021). There are already genetic experiments happening using CRISPR technology, and it is only a matter of time before it makes its way to the field of ecology for experimentation.

On a small scale, there are already similar experiments happening in the ecological field now. Fritts (2022) reports of a conservation group which has been dedicated to keeping the black-footed ferret population alive and well since the 1980s. They noticed recently that because their conservation effort started when black-footed ferrets were on the brink of extinction, the gene pool for the species is dangerously lacking variation. Variation is healthy for populations, and this population–where all of the ferrets descended from the same 7 ferrets–didn't have much. Fritts states that to combat this, frozen black-footed ferret DNA from a ferret that died over 50 years ago is being cloned via somatic cell nuclear transfer to re-introduce new alleles to the population as an attempt to manually change the gene pool. This experiment in and of itself is not gene editing, but it's close and shows the direction that the field is heading in. Once technologies like CRISPR are more commonplace, they will eventually become staples of ecological experiments like genome sequencing already has.

DISCUSSION

The use of genetic technologies as they have been advancing has had many positive impacts on what scientists are now able to see and understand. Previously, the function of genes in gene theory was postulated by Mendel (1865), but now the specifics of how genetics work is clearer than ever. Using the information found by geneticists, ecologists are now able to see and understand things that were unknown in the past. Darwin (1882) looked at slight differences in finch species in the Galapagos and questioned how and why they could have diverged so slightly. His thoughts became the beginnings of the theory of evolution and natural selection, but other scientists couldn't visualize how it was happening like Darwin could, and therefore had a hard time accepting what Darwin proposed as true. The integration of using genetic technologies to "see" the submicroscopic genomic elements that we couldn't before is what has allowed the field of ecology to advance so far so quickly. Without the genetic tools to explain the differences in species, the reason for animal characteristics and behaviors, or the evolutionary pathways of different organisms, the field of ecology would still rely on physical evidence to estimate why species are the way that they are, rather than reading the genetic material that has all the information we need encoded within it. The history of genetic technologies being used in ecological study and experimentation can also help predict that new and improving genetic technologies like CRISPR will eventually make their way into the ecological field of study as well.

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