THE USE OF PHENOTYPIC IMAGE PROCESSING TO GENETICALLY MODIFY CROPS

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Abstract—With the continuous increase in our planet's population, the demand for food and agricultural resources becomes a growing concern. This paper will describe and evaluate the importance of phenotypic image processing of crops, a more sustainable and efficient method that allows farmers to increase overall crop yield. By applying light sensors to the plant, scientists can see how different genotypes play key factors in the growth and development of agricultural resources. By utilizing phenotypic image processing, engineers can determine specific traits of plants and genetically modify them to bolster productivity in their respective, sometimes unfavorable, environments. Scientists can then study interactions between genotypes and the environment. After studying these interactions, certain phenotypes of plants with high stress tolerance or high yield can be isolated, to gain quantitative information. This allows them to produce genetic modifications that will increase overall yield, and therefore improve social, economic, and environmental sustainability.

The process of phenotypic image processing is fulfilled through the use of machine learning algorithms at specific wavelengths. Several methods of plant phenotyping, each using a different light sensor (various wavelengths), are employed. Phenotypic image processing can be exploited to assess and improve various plant functions, such as photosynthesis. Furthermore, companies such as Benson Hill and Becks Hybrids, have partnered together to apply this technology in the aspect of increasing corn yields for farmers. As a result, we hope to convey the importance of making a sustainable world, that will continue to prosper for as long as possible.

Key words—crop modification, genotypes, phenotypic image processing, phenotypes, photosynthesis

INTRODUCTION: WHY PLANT PHENOTYPING?

Many resources come and go in terms of their relevant importance to society, but one that is constantly demanded across all parts of the globe are food products. Due to their necessity in society, scientists have begun to develop ways to produce more, with less given materials. This focus of increasing efficiency has led us to the process of genetically modifying organisms to meet specific needs and desires. Genetically modified organisms, GMOs, are organisms whose genetic material has been altered by means of genetic engineering. As a result, the genetic composition of individual organisms can be altered in order to show specific traits that may be lacking otherwise. One of the main technologies involved with genetic modification is phenotypic image processing. In terms of genetics, genotypes are the specific genes that make up your chromosomes, while phenotypes are the traits in which they produce. The process behind this technology involves the use of various light sensors to capture wavelengths of isolated, high yield plants, in order to observe and monitor several phenotypes that make up the basic structure of the plant itself. This scientific breakthrough has allowed scientists to piece together what causes certain plants to be more productive in some environments, while being much less productive in others.

The basic structure of phenotypic image processing can be described using a 5-step process. In short, the 5-step process involves image acquisition, pre-processing, segmentation, features extraction, and ML classification that all work to provide scientists with the material they need in order to produce these complicated, genetically modified organisms. The process begins with the use of various light sensors to capture specific wavelengths of reflected light. Depending on the light sensor, or camera, that captures the image each of the following four steps will vary due to the utilization of different software that makes the analysis of phenotypes possible. The 5-step process paves the way for the ability of crop production in the near future. With the ability to allow plants to function more efficiently, humans can produce more food than initially possible. As a result, the world can continue to feed the ever-growing population with increased certainty.

THE SURGE IN WORLD POPULATION

Since as early as 10,000 B.C., Homo Sapiens have used simple farming methods in order to grow their own crops, and provide for their families. However, as times change and the demand for agricultural resources rises, the supply of these crops can quickly dwindle unless modern technological methods are implemented. Currently, modern farming involves the use of large-scale equipment such as sprinkler irrigation systems, tractors, and harvesters in order to quickly grow, harvest, and replant crops for the upcoming season. This technology can be very expensive, and can set farmers back on their schedules if problems were to arise in their operation. Along with this, limiting the use of fertilizers and pesticides can help to sustain the agriculture and farming practices of the modern era [1]. As a result, modern farms averaged a total of 441 acres in size in 2015, and leave us begging the question "Can we keep up this means of production in the future?"

Currently, planet Earth is home to 7.5 billion people, all living in different parts of the world. Although, this wasn't always the case. As you can see in figure 1, 1959 demonstrated a time in which the world population was estimated to be around 3 billion people. This number rapidly increased by 1999 to a staggering 6 billion [2]. Therefore, the population doubled in the span of only 40 years.

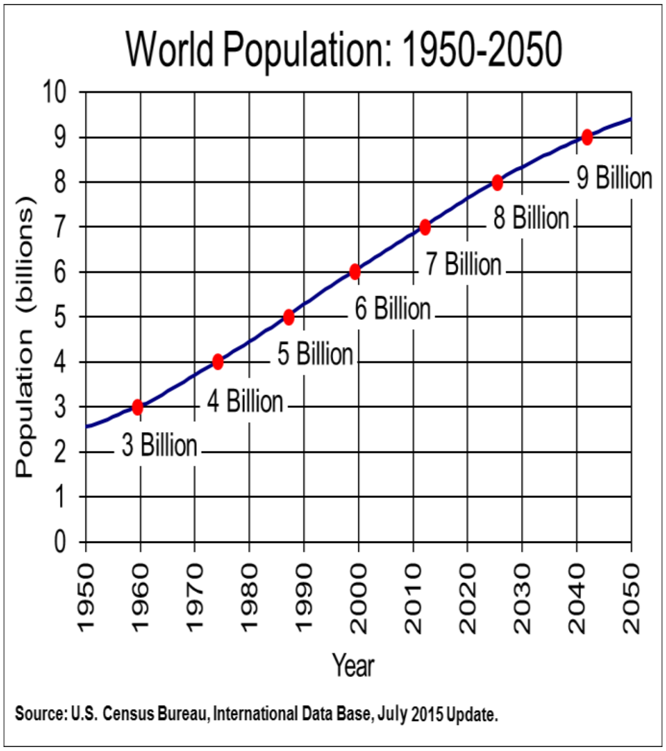

FIGURE 1 [2]
Current world population including projections through 2050

As a result, scientists have begun to predict that by 2044, we could potentially see an increase of 50%, thus making the population closer to 9 billion in total [2]. This rapid influx could potentially have harmful impacts not only to the environment, but also to the food resources we have been able to provide. By increasing the population at such a rapid rate, available global farmland will be removed in order to accommodate the growing number of people. According to research done at the University of Florida, figure 2 shows that there has been a 6.6 million acre decrease in farmland between the years of 2008 and 2015 [2]. Although this research also suggests that average farm size has increased by 20 acres during this same period of time, this leads us to believe that with less farm owners around the globe, the need for improving productivity to keep them sustained is of utmost importance.

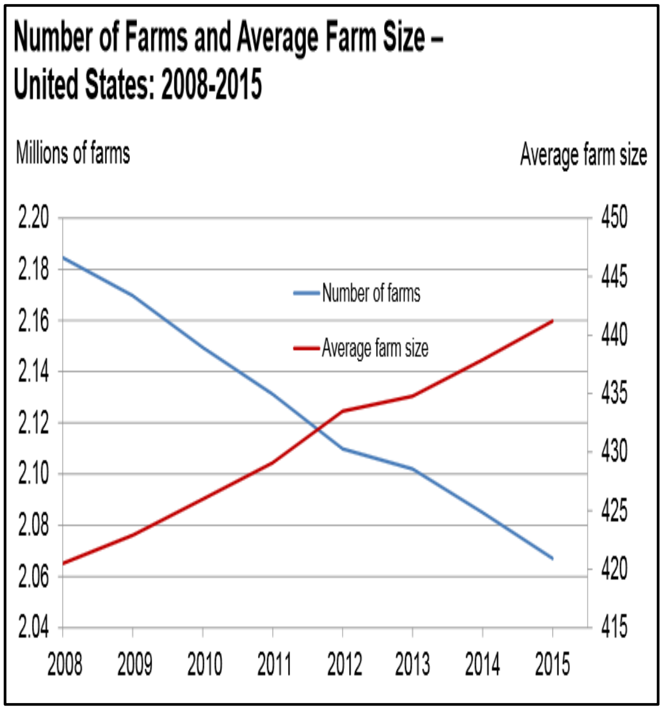

FIGURE 2 [2]
Graph depicting relation between average farm size and number of farms in the United States

As a result, modern farming methods will no longer be available to use, if we don't have the room necessary for large scale equipment. Therefore, scientists have begun to shift focus into trying to develop methods that can increase production and yield of crops, with much less available farmland for farmers. One such method involves the use of genetically modifying the organisms themselves, GMOs, in order to ensure that they are growing at their highest and most efficient means.

WORKING TOWARDS A SUSTAINABLE FUTURE

As scientists and engineers develop new technologies to improve life on a global scale, the importance of accounting for long term impacts, becomes of growing concern. The term sustainability in modern advancements "satisfies the needs of the present generation, without compromising the ability of future generations" [3]. Therefore, by making effective use of the resources available to us, future generations will also be able to continue growing and advancing to maximize productive potential on the world in which we live.

Sustainability can be divided into three main subsections: Social, Environment, and Economic. The term social sustainability encompasses all human activities, and refers to the ability to create successful environments that promote wellbeing, to ensure that everyone is given the opportunity to satisfy their "aspirations for a better life" [3]. Social sustainability attempts to limit the overexploitation of resources in society to ensure that the essential needs of people in the future will be met in a similar fashion.

The second type of sustainability refers to the effective impact of resources on the environment. Before modern human infrastructure, environmental sustainability was largely impacted by the natural systems within the environment. However, recent interventions are becoming more drastic, and more impactful to the life expectancy of natural systems including "the atmosphere, the waters, the soils, and the living beings" [3]. Overall, the harmful impacts of human development are causing harmful limitations to the development of the ecosystems and land around us.

Finally, meeting essential needs depends on the ability to achieve full growth potential within all societies across the globe. Economic sustainability can only be pursued if demographic regions across the globe suggest changes to productive potential and overall wellbeing. According to the United Nations Documents, "an expansion in numbers can increase the pressure on resources and slow the rise in living standards in areas where deprivation is widespread" [3]. Overall, by effectively making use of the resources we have, and protecting the ones we lack, the ability to create a livable environment for the future is very much possible.

HISTORY OF GENETIC MODIFICATION

Although GMOs haven't been talked about for very long, genetic modification has technically been around for more than 30,000 years. Since 30,000 B.C., humans have altered the genetics of organisms in the form of selective breeding for animals [4]. Selective breeding was a process that allowed farmers to selectively breed their livestock in order to ensure that specific traits, adept to farming, would be passed down to the next generation. Some such traits included growing larger and producing more meat/wool to allow farmers to profit more from their bigger sizes. However, it wasn't until 1973 that the scientific research behind genetically modified organisms began to take shape into what we know today, after the creation of the first genetically engineered. Scientists Herbert Boyer and Stanley Cohen successfully cut out a gene from one organism, and were able to transfer it into another [4]. A timeline of the most important events in the history of genetic modification can be shown in figure 3. These scientific breakthroughs paved way for the genetically modified organisms we see today all around us.

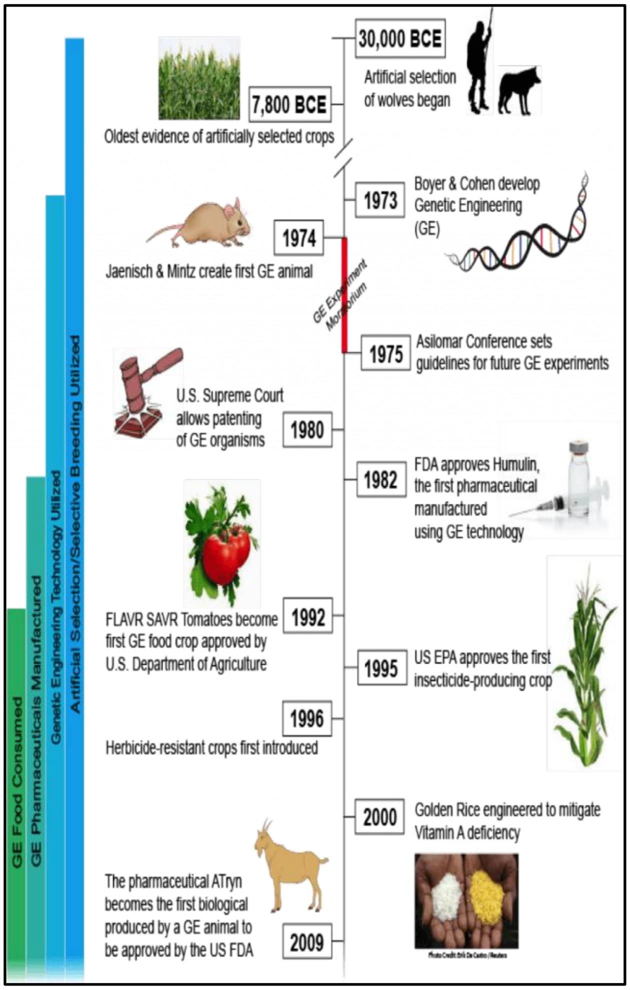

FIGURE 3 [4]
Timeline representing the historic events from early forms of selective breeding to modern uses for GMOs in food resources

GMOs are all around us in modern society making up the vast majority of corn and soy-based products found in local supermarkets [4]. However, GMOs have led to large debates in recent years over their health concerns and whether or not genetically modified food products should have to be labeled in stores. These debates relate mainly to the idea that GMOs can introduce new toxins that are trying to effectively eliminate other toxins from entering the body during consumption of basic foods [4]. However, most genetically modified organisms are used primarily to increase shelf life of products and prevent simple mutations such as bruising in potatoes to occur. All in all, the genetics behind food resources has grown rapidly in the last decade, and will most likely see similar numbers, as scientists attempt to feed the ever-increasing world population [2].

THE SCIENCE BEHIND PHENOTYPIC IMAGE PROCESSING

What is Phenotypic Image Processing

Plant phenotyping is a way of studying how plants interact with their environment. Not long ago, plant phenotyping was performed manually, which proved quite arduous and inaccurate. Phenotyping has evolved from the use of tools, such as rulers and weighing scales, to the use of light sensors, hyperspectral cameras, and detail-oriented image processing software. According to the Indian Society for Plant Physiology, by means of this advanced technology, quantitative measurements of phenotypes and their description are taken to understand the complex interactions between sets of traits and the environment [1]. A research paper published by Frontiers in Plant Science states, “The outdated phenotyping procedures- a technique dealing with plant characteristics, in conjunction with available genetic information, have not allowed a thorough functional analysis and have not led to a functional map between genotype and phenotype” [5]. This paper goes on to explain how high-throughput plant phenotyping allows for phenotype data to be extracted from plants in a non-destructive manner [5]. High-throughput simply describes a process where the technology is able to sequence masses of DNA through automation and large-scale data analysis [5]. A BioMed Central research paper describes that in modern plant phenotyping, a high-throughput process, DNA is transcribed into RNA, which leads to the formation of proteins, and this transformation effectively determines the phenotypic traits of the plant [6]. Figure 4 shows the relation between genotype and phenotype. The purpose of this image is to convey that genotypes may respond differently to varying environments, which results in different phenotypes. Due to the sequential alteration of the transcribed genes and their proteins, differences in plant physiology and morphology arise [6].

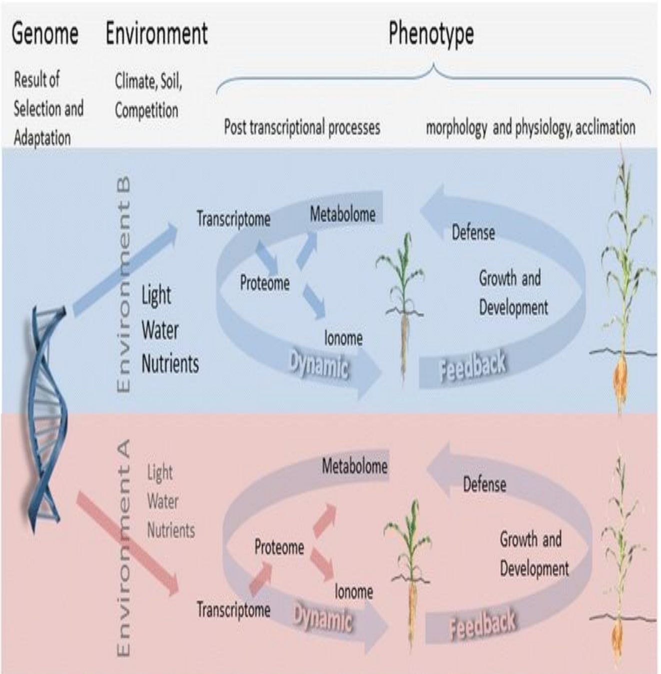

Figure 4 [6]
The relationship between genotype and phenotype of the plant

Through the utilization of phenotypic image processing, plant phenotyping has become much more efficient and accurate, which will be distinguishable throughout this section and the next.

Phenotypic image processing of plants represents the most recent technology for improving crop yield. This process allows for plants to be genetically modified in such a way that bolsters productivity and strengthens them according to their various environmental factors. Engineers isolate phenotypes of plants with high stress tolerance and high yield, compiling quantitative data, which is then analyzed through use of machine learning (ML) algorithms. A Sensors article say that the engineering software that uses ML algorithms may require user inputs such as manual point selection, whereas others are automated or semi-automated [7]. It goes on to explain that ML algorithms that are based on a color model or threshold value are used for clustering pixels in the segmentation process, which separates the object of interest from its surroundings [7]. According to a Nature Methods research article, the use of images that provide an unbiased source or quantitative data is known as morphological profiling [8]. Morphological profiling allows for the full spectrum of the plant to be observed, as several different features are implemented to provide the most accurate image analysis. The Nature Methods article claims that the image includes "not only metrics of shape but also intensities, staining patterns, and spatial relationships" [8]. Phenotypic image processing represents an application of morphological profiling, which has the benefits of providing an extremely detailed and accurate analysis. The extreme accuracy and detail is in part due to the technology employed during the pre-processing stages.

Various light sensors, which capture different wavelengths of light, are used in conjunction with hyperspectral cameras to capture the initial image. A Sensors article says, "The aim of imaging is to measure a phenotype quantitatively through the interaction between light and plants such as reflected photons, absorbed photons, or transmitted photons" [7]. Healthy plant leaves interact with electromagnetic waves, or detection information carriers, differently than infected plants. Light sensors are able to detect these differences which is why colors may appear brighter or different bands of light can appear altogether [7]. For example, healthy leaves with high water content (emissivity between 0.97 and 0.99) emit infrared radiation based on temperature and reflect green light (550 nm) effectively when compared to other bands of light, which are absorbed by photoactive pigments within the leaf [7]. This explains why a healthy leaf appears green to a red-green-blue imaging sensor as well as the naked eye. The various sensors enable several phenotypes to be monitored in all regions of the plant. This is due to the specific range of light wavelengths that each senor is designed to capture. A paper published by the Indian Society for Plant Physiology states, "advanced sensors not only monitor physical state of plants (i.e., growth) but also to a great extent their functional, molecular and biophysical processes, as they change in response to genetic mutation or environmental factors" [1]. This is the simple, yet critical reason, that various light sensors are implemented for plant phenotyping. The research paper by the Indian Society for Plant Physiology continues on by separating the light sensors into two main groups: shoots (above ground) and roots (below ground) [1].

An additional grouping convention can be used to distinguish the sensors based on their quality and performance. The first class is red-green-blue (RGB) imaging (~400–700 nm), which measures "growth rate, morphology, structure, chlorophyll content, nitrogen content" for shoot phenotyping and "root growth, branching, kinematics of individual roots for root phenotyping" [1]. Infrared (thermal) imaging (~750–1300 nm) measures "stomatal response, water deficit, and disease incidence" [1]. Spectral reflectance (fluorescence) imaging is mainly associated with leaf function involving "pigments and their activity, water deficit, nitrogen content, plant biomass, and disease incidence" [1]. The final class consists of a broad range of light sensors that monitor the architecture and physiology of the root system [1]. The large variety of light sensors conveys that each sensor is implemented to focus on different phenotypes of the plant, which allows for nearly every aspect of plant morphology and physiology quantized and analyzed thoroughly by the completion of phenotypic image processing. Figure 5 shows the use of RGB, hyperspectral, and Chl fluorescence imaging to analyze an *Arabidopsis* plant, with the control being water and the salt stressed being treated with 250 mM NaCl [9].

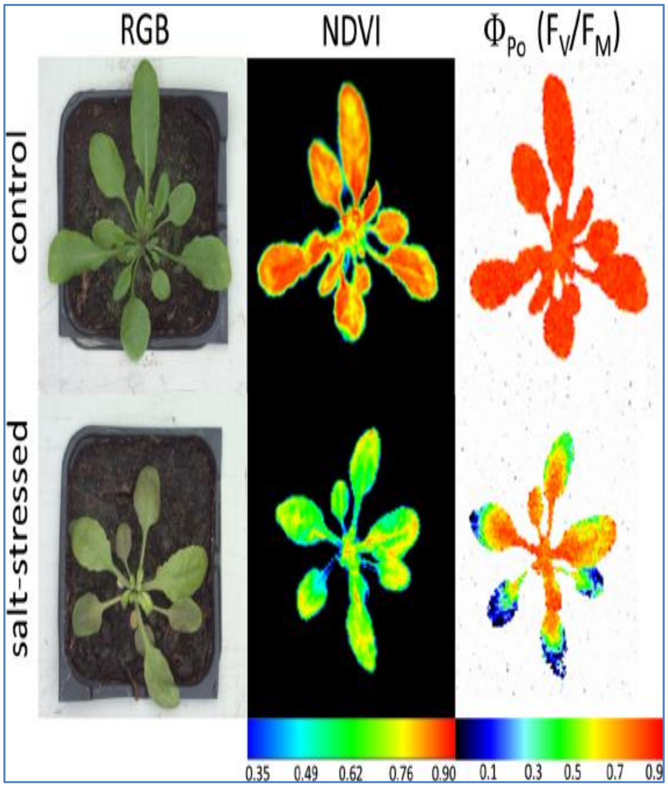

FIGURE 5 [9]
Images of *Arabidopsis* plant using different sensors

As depicted in this figure, clear differences exist between the control group and the salt-stressed group, as well as between each of the sensors. The RGB image can be used for "computation of rosette area or shape parameters" [9]. The hyperspectral image shows "spatial distribution of vegetation index reflecting changes in the chlorophyll content" [9]. The longer wavelengths are reflected by the leaves of the properly watered plant, suggesting that the chlorophyll is in a good state. In the salt-stressed image, the longer wavelengths of light are absorbed, which is why no red light is reflected and chlorophyll content is worse off. Lastly, the Chl fluorescence image reveals changes in maximal quantum yield, which reflects photosynthetic activity [9]. Clearly, when red light is most efficiently reflected, it can be concluded that photosynthesis will be most productive. Overall, figure 5 provides a basic example of the importance of using different light sensors to isolate every phenotype.

The 5-Step Process

Phenotypic image processing can be explained in five main steps: image acquisition, pre-processing, segmentation, features extraction, and ML classification. While this process can be summarized in only five steps, it is quite complicated and uses complex technology and image analysis software. This cutting-edge technology is necessary for high-throughput phenotyping to occur, which makes phenotypic image processing the most efficient and sustainable method for plant phenotyping. Figure 6 outlines the five-step process, including the various components of each step and a sample of the result of each step.

FIGURE 6 [10]
Basic workflow of phenotypic image processing

Image acquisition through use of various light sensors was briefly described in the previous section, and the final result of phenotypic image processing was also described with the mention of intensities, staining patterns, and spatial relationships. In this section, the steps that take place in between the initial image acquisition and the completion of the image processing that finally allows for the production of a genotype will be explained in detail.

Image acquisition represents the first step in phenotypic image processing. The initial digital representation is obtained through an imaging sensor, or camera. A research paper published by Gigascience explains that these imaging sensors, or light sensors, mainly operate on a charge-coupled device (CCD) or a complementary metal oxide semiconductor (CMOS) [10]. When the sensor captures a specific light wavelength, a major or minor charge is “amplified, filtered, transported, and enhanced by means of specific hardware” [10]. This comprises the formation of pixels of the image as taken by the camera. In conjunction with CCD or CMOS imaging, time delay and integration (TDI) improves image acquisition by increasing speed and sensitivity, especially in extreme lighting conditions [10]. The research done by Gigascience also states, “CCD, CMOS, and TDI, confer unique characteristics, which define the type of data a camera can provide with a degree of robustness” [10]. This basically means that each imaging sensor has strengths and weaknesses that make one a better option than the other in certain situations. CDD imaging sensors produce higher quality images in low light settings and has a better dynamic range which provides better depth of color, while CMOS sensors process images faster and are cheaper [10]. When these lenses capture specific wavelengths of light, the CDD and CMOS sensors act as the aforementioned “light” sensors, such as RGB, infrared, and fluorescence imaging.

Multispectral and hyperspectral cameras are becoming more commonly used for image acquisition in phenotypic image processing. Because these devices can capture images from a number of discrete bands, the images can have higher resolution due to possibly hundreds of bands being registered in a single pixel [10]. Fintan Corrigan, a drone expert who combines his passion with agriculture and technology used in phenotypic image processing, explains that these cameras work by using reflectance properties of vegetation, combining two or more wavelengths of light, to create vegetation indices (VIs) [11]. The different vegetation indices allow for various relations between plant and environment to be analyzed. Figure 7 shows a relatively small amount of vegetation indices and their corresponding wavelengths. Each of these indices can be taken advantage of to analyze certain plant material.

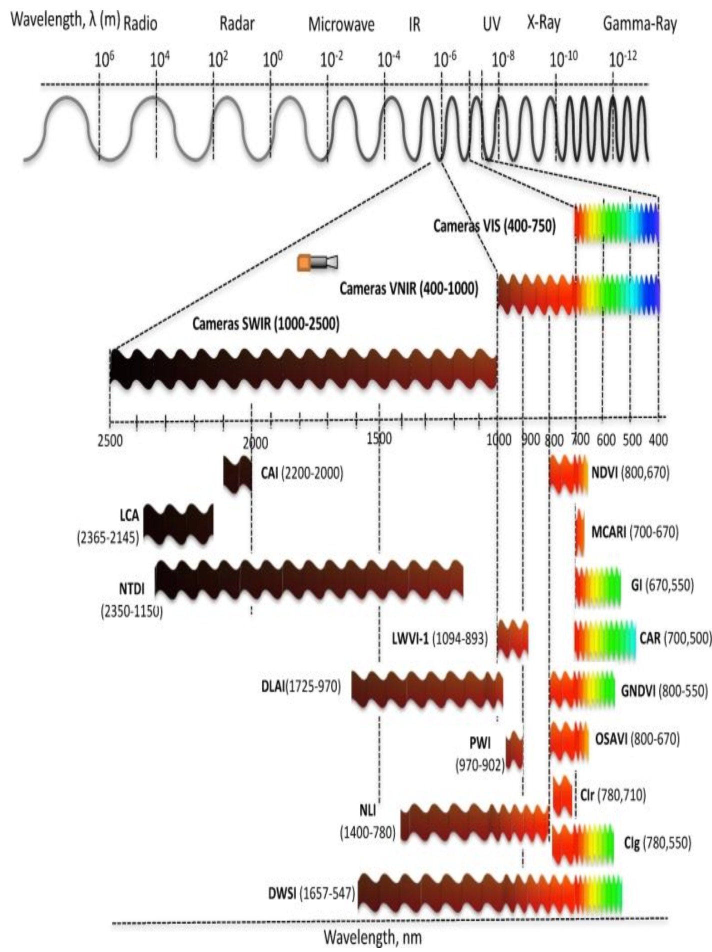

FIGURE 7 [10]
A few vegetation indices of multispectral cameras and corresponding wavelengths

In addition to the imaging sensors previously mentioned, Time of Flight cameras (ToF), LIDAR systems, and tomography imaging also contribute to phenotypic image processing [10].

After the acquisition of the raw image, the image then undergoes the pre-processing stage. The research paper published by Gigascience elaborates on this stage. The paper affirms that the goal of pre-processing is to enhance the object of interest by enhancing contrast and reducing noise, which allows for a more accurate analysis of the image in a later stage [10]. The Gigascience research mentions some operations involved in pre-processing, such as “image cropping, contrast improvement, or other significantly more complex operations such as dimensionality reduction via principal component analysis or clustering” [10]. Different pre-processing methods can be employed, depending on which light sensor was used in the image acquisition stage, as well as the raw image conditions. The pre-processing method that is chosen for a specific image should be the method that will best improve image analysis.

By enhancing the object of interest in pre-processing, the image is ready to undergo the third step, which is segmentation. Gigascience research describes segmentation as the ability of the image processing software to discriminate the object of interest from the background through use of algorithms [10]. These algorithms function based on the "internal similarity of pixels in parameters such as texture, color, statistic" [10]. A Nature Methods research paper suggests that pixels are grouped together by the algorithms to distinguish the plant cell from surrounding cells [8]. Various algorithms are used for segmentation, each algorithm applied for a specific type of background or surrounding objects from the initial image acquisition. With the conclusion of segmentation, the actual data analysis process commences.

The fourth step, feature extraction, constitutes the acquisition of raw data. A Nature Methods paper suggests the importance of this stage by mentioning that phenotypic characteristics are measured during feature extraction [8]. Gigascience research defines a feature as, "information that is used to resolve a specific computer vision problem," and, when extracted from the image, is retained in "feature vectors" [10]. Similar to segmentation algorithms, a multitude of feature extraction algorithms exist and are used in combination to extract certain features. According to a Nature Methods publication, the main features extracted can be categorized by shape, intensity, texture, and microenvironment/context [8]. Shape features include standard shape and size measurements of the segmented cell, such as "perimeter, area, and roundness" [8]. The intensity-based features include the quantization of mean and maximum intensity by measuring the intensity of each cell [8]. Texture features "quantify the regularity of intensities by use of mathematical functions, such as cosines and correlation matrices" [8]. Lastly, microenvironment and context features quantify spatial relations between segmented constituents [8]. Cell profiling with hundreds of combinations of feature extraction algorithms results in an accurate phenotype.

Feature extractions set up the final stage of phenotypic image processing, known as ML classification, which proves essential in classifying phenotypic image processing as "high-throughput." Gigascience research suggests that ML tools are optimal for large-scale data analysis because they "identify patterns using combinations of factors instead of performing independent analysis" [10]. ML libraries have been compiled in languages such as R, Python, Java, C, and C++ [10]. Gigascience research also mentions that deep learning (DL), derived from ML, uses a set of algorithms to "model with a high level of abstraction," which brings phenotypic image processing one step closer to artificial intelligence [10]. Once ML classification is complete, the phenotype has been isolated, and biologists then use the phenotypic data to produce the desired genetic modification aimed to improve production.

FOSTERING IMPROVEMENTS TO PHOTOSYNTHESIS

Genetic modifications by the use of phenotypic image processing have been vital in remodeling how plants can effectively undergo photosynthesis. The term photosynthesis is used to describe the process by which plants take in sunlight, and are able to convert it into chemical energy that they can use to fuel other activities. In recent research by Dr. Stephen Long at the University of Illinois, phenotypic image processing can be implemented in society as a way to ensure that plants are being as efficient as possible with the process behind photosynthesis. In his finding, Dr. Long concluded that "light saturated photosynthetic rate is commonly lower in species with thinner leaves" [12]. Therefore, he was able to conclude that plants with thicker leaves are able to efficiently use more of the light resources that they take in from the sun in order to create more glucose molecules following the process of photosynthesis. Furthermore, Dr. Long found that increased CO_2 can have two major impacts on C_3 plants: "an increase in plant leaf photosynthesis and a decrease in stomatal conductance to water vapor" [12]. This proves that organisms living in parts of the world with higher carbon dioxide emissions are able to take in more water and CO_2 molecules through the stomata, therefore having the ability to grow larger. Finally, the last part of his research proved that the shape of leaves can have an important influence on the rate of photosynthesis. According to figure 4, Dr. Long proved that plants with leaves are a 75-degree angle will distribute the light energy equally among all leaves in the plant, penetrating to lower levels of the canopy. Therefore, the efficiency will be over double that of plants with flat leaves during midday in full sunlight [12].

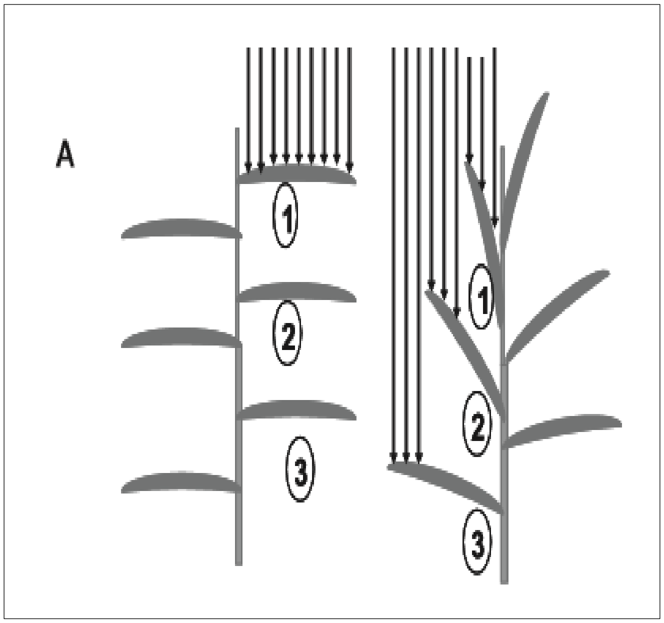

FIGURE 5 [12]
Distribution of light energy being taken in by plants, dependent on the shape of their leaves

All in all, this research can be vital to the application of phenotypic image processing because it can provide evidence that there are possibilities available that can promote larger crop yields for farmers.

Although photosynthesis was at one point viewed as being too complex to genetically alter, research by Dr. Long has proven otherwise. In an attempt to push the boundaries of photosynthesis, companies such as Benson Hill and Beck's Hybrids have partnered together to develop a trait that allows corn plants to absorb more carbon from the atmosphere [13]. Initially, "The photosynthetic process plants devised themselves was built to survive," proving that plants didn't survive to "yield more, they survived to reproduce" [13]. However, Benson Hill and Beck's Hybrids believe that they can modify the DNA of corn, to allow the individual kernels to grow larger and more readily per ear. As a result, instead of having to expand farms outwards to feed the growing population, crops can grow larger in a smaller, more protected environment. Beck's Hybrids plans to license the trait to seed companies starting in the mid-2020's, once it is commercialized [13]. With increased focus on global food scarcity, the focus has begun to shift towards ensuring that humans can productively provide for themselves, even as populations continue to rise, and available land continues to shrink.

THE APPLICATIONS OF THIS TECHNOLOGY IN THE MODERN WORLD

A major factor in the science behind how the Earth works, involves global differences in the environmental factors that define a particular region. Since the earliest forms of farming, producers have grown crops that are suitable in their particular conditions around the globe. As a result, farmers are able to maximize harvest, and therefore, net the greatest yield. However, this is not always possible, such as in regions that lack fertile soil, or have other environmental stress factors limiting production. One example of this is drought. Not only does a drought limit the amount of water the surrounding soil can consume, it can also have a permanent impact on the fertility of the soil years later. Also, saline soils, soils with high salt contents, are currently having a drastic impact on the potentially useful agricultural land of Southern Asia [5]. Although these factors can't be stopped entirely, scientists have begun to use phenotypic image processing in order to study how plants are able to react which the environment around them. Scientists can then extract genetic material from the cells of the plant, in order to help increase their productivity in these respective environments. By implementing beneficial genetic material into the cells, plants can develop better ways to cope with environmental stresses in the future.

With the science behind phenotypic image processing, the modern applications in today's society will help pave way for agricultural success in the near future. The biggest factor for phenotypic image processing is time. In a world in which population is constantly increasing, the need for agricultural resources becomes of growing concern. To satisfy this rapid increase, it is important to establish the connection between plants genotypes, and the specific phenotypes that are seen as a result [5]. However, in underdeveloped regions, they don't necessarily have the technology available to protect their crops from major disasters that can strike at any given time. Although this is only one application of phenotypic image processing, the overall goal remains the same: to allow crops in varying regions across the globe, to grow as efficiently as possible. In the previous section, the application of this technology was discussed using Benson Hill and Beck's Hybrids as an example. However, allowing food to grow larger is not the only beneficial trait of genetically modifying organisms. According to Consumer Reports, "A new form of salmon that is genetically altered to grow to maturity twice as fast as wild salmon," is currently being tested by the Food and Drug Administration, FDA [14]. This technology could allow underdeveloped countries to receive larger quantities of food in a shorter period of time. Along with this, genetically modifying organisms can help to eliminate any unwanted or unnecessary mutations to crops. The FDA recently discovered advancements in potato crops in order to prevent bruising and have lower levels of acrylamide. Acrylamide, a carcinogen that can be produced when cooking potatoes at high temperatures, can be removed entirely with the application of phenotypic image processing [14]. All in all, the science behind phenotypic image processing not only leads to increased crop yields but can also have a large impact on improving the safety and nutritional values of the foods in which we consume.

PHENOTYPIC IMAGE PROCESSING AIDS IN SUSTAINABILITY EFFORTS

The idea behind economic growth is largely influenced by the changes to the Earth's ecosystems. According to the United Nations documents, "ecosystems everywhere cannot be preserved intact," meaning that in order for the human population to continue growing, we must use the resources provided to us in a methodical manner, to minimize overall depletion [3].

Agricultural resources are an example of a renewable resource that can be replanted upon harvesting. However, these crops can only grow in environments in which the soil contains the correct nutrients to allow for photosynthesis to occur. Therefore, with the continued decline in available land, the importance of sustaining crop production by improving overall yield increases. In recent years, phenotypic image processing has allowed scientists to genetically manipulate the genes of plants, in order to provide them with the most beneficial genotypes to suit their respective environments [1]. In doing so, farmers can produce a greater net yield per harvest, therefore providing the world population with the resources they need in order to be economically stable.

Along with improvements to economic stability, the genetic modification of organisms has also aided in the development of environmental stability. Over time, humans have had a drastic impact on the natural resources available to them. For example, the release of pollutants by large scale organizations have caused water systems and the atmosphere to decrease in overall quality [3]. Although this impact may seem small now, in terms of developing a sustainable future for Earth, it could have harmful impacts further in the future, depending on how the surrounding ecosystems adapt to the change in conditions. By incorporating phenotypic image processing technology, scientists have developed ways to improve the efficient use of agricultural resources. As a result, long-term sustainability of the world's ecological needs can help combat the issue of increasing global population [2].

Lastly, the use of phenotypic image processing in agriculture has allowed underdeveloped countries to increase their productive potential, and therefore begins to satisfy their need for a better life. These improvements to social sustainability have the potential to "encourage consumption standards that are within the bounds of the ecological possible and to which all can reasonably aspire" [3]. As a result, the satisfaction of overall human needs can be met not only for the current generation, but also for generations to come.

CONCLUSION: GMO'S FOR A BETTER WORLD

Often overlooked, the need to improve accessibility to food resources is becoming increasingly important in modern society, as we fight to ensure that the world population can be properly fed. Although this is not always the case, with global populations set to rise 50% by 2044, scientists seek answers as to how we can produce more, with less available space to grow and maintain crops [2]. The main goal of production is to make the best use of the opportunity cost of producing a particular good. As a result, food resources are constantly traded among different countries because the opportunity cost of producing a crop in one country might be smaller than for another country. Therefore, increased production and yield, can help lead to a better, more efficient economy.

With the recent use of phenotypic image processing, scientists have begun to extract DNA from specific crops with highly favored traits, and implement the same genetic material into other crops, in order to improve overall productivity. This increase in efficiency will therefore provide a variety of benefits to society including greater crop yield, decreased amount of time to mature, and decreased toxins that could potentially be harmful for human congestion.

Although phenotypic image processing is growing in popularity, many still fear the incorporation of genetically modified organisms into the food resources we consume. Recent laws regarding labeling have been implemented across the United States in order to disclose full information to consumers regarding what is in the foods they are purchasing [14]. This method of labeling can be beneficial in terms of disclosing full information to consumers, but could also cause many to resist buying these products entirely. Overall, a label could explain that a GMO product is still as safe to consume as a non-GMO food by including specific ramifications as to the chemicals went into the production, and the overall purpose for doing so. With more disclosed information, the future is bright for phenotypic image processing to soon allow farmers all across the globe to grow crops that they can ensure, will be best suited for the environment, and will maximize overall yield.

Engineers seek to continue improving the technology involved with phenotyping image processing to make it more efficient and sustainable. Current high-throughput plant phenotyping with phenotypic image processing has already proven to be a method that will greatly benefit the entire world as population continues to grow. Leading companies in nanoelectronics, such as IMEC, are combining the best features of CCD and CMOS with TDI to create higher quality imaging sensors [10]. Also, by using ML technology combined with molecular techniques, high-throughput plant phenotyping will continue to develop rapidly and data collection methods will evolve with the growth in phenotypic image processing [5].

Phenotypic image processing in plants currently plays a large role in developed countries seeking to improve their agricultural benefit across the globe, however the future for phenotypic image processing is bright. If this technology were to continue to increase in popularity, it could potentially spread to regions in need, and set them on the right track towards becoming successful.

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