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Profile

George Washington Carver: A plant scientist's perspective

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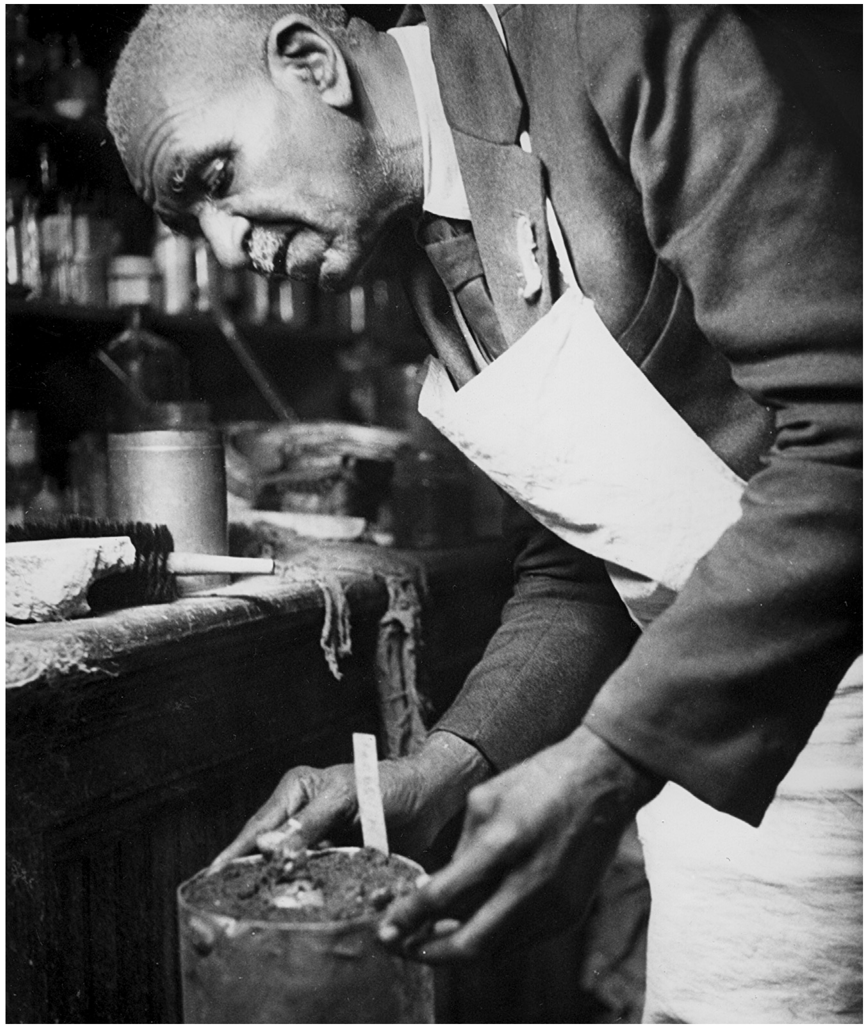
"The study of Nature … is the only true method that leads up to a clear understanding of the great natural principles which surround every branch of business in which we may engage." Extracted from 'Progressive nature studies' by G.W. Carver (1897).

Biographies about George Washington Carver describe a Black, thin-skinned and frail boy, traded for the price of a horse, who grew to become one of the most famous influencers in US agriculture. The struggles, brilliance and fortuitous incidents that characterised Carver's life and work are exposed in websites, books, podcasts and on social media, and have inspired the name of more than 10 international organisations. The aim of this profile is to highlight the impact of Carver's contributions to modern plant science and to celebrate his achievements as a pioneering interdisciplinary researcher. By discussing his work, in light of recent discoveries in legume symbioses and soil nutrition, the goal is to reveal his foresight and relevance, inspire new generations from diverse backgrounds and contribute to the decolonisation of the curriculum in higher education.



George Washington Carver working at Tuskagee University, Alabama, in September 1938: Photo courtesy of the National Archives and Records Administration.

An introduction

George (named Carver after the owners of the farm where he grew up) was born in the early to mid-1860s just prior to the abolition of slavery in Missouri in 1865[1]. He attended a school for African American children while working nights and excelled in Art. He graduated from high school aged 21 years old and was awarded a scholarship to attend the Highland University of Kansas. This institution refused to enrol him after learning that he was Black, but Carver continued his education in Iowa's Simpson College and later at Iowa State College, where at 30 years old he was appointed a faculty member. In 1896, he obtained an MSc degree in Agriculture for his work in fruit hybridisation. Soon after that, he met Booker T. Washington (a leader of the African American community, educator and adviser to multiple US presidents), who persuaded Carver to join the Tuskegee Institute: the first African American school of higher learning in America. At Tuskegee, Carver was head of the Agricultural Experiment Station, built the department from scratch and developed the research that would later revolutionise southern agriculture. Carver's research focused on finding alternatives to rejuvenate the land that had been destroyed by cotton plantations and explored the potential benefits of re-introducing native crops and legumes.

Carver's research findings and outreach activities made an impact on the lives of farmers and in society[2]. Perhaps the most relevant event was in 1921 when Carver was asked to speak at the House of Ways and Means Committee and was able to secure the highest protective tariff for the peanut industry, a move that dubbed him 'The Peanut Man'. In 1916, Carver was named a Fellow of the Royal Society of Arts in London and, in 1923, he won the Spingarn Medal for outstanding achievement by an African American. He met Henry Ford (the industrialist founder of the Ford Motor Company) in 1937, who soon became Carver's close friend and biggest investor. Ford set up a lab for Carver in 1942 to experiment with different crops and this work eventually led to the discovery of a substitute for rubber from goldenrod, a plant weed. With his savings, Carver established a museum and a foundation (founded at

Tuskegee) to develop uses for agricultural waste and to create food products.

George Washington Carver died on January 9, 1943 in Tuskegee[1]. In 1953, a national monument was erected (the first monument for a Black man) at his birth site. The epitaph read: “He would have added fortune to fame, but caring for neither, he found happiness and honour in being helpful to the world”. Thirty-five years after his death, Carver was elected to figure at the Hall of Fame for Great Americans. His face appeared on US commemorative postal stamps in 1948 and 1998, as well as on a commemorative half dollar coin minted between 1951 and 1954.

George Washington Carver is in fact the most prominent Black scientist from the early 20th century. A lot has been written about his life, but his contributions to plant science and their impact on today’s research are often forgotten or poorly recognised outside the US. This profile aims to fill this gap by reviewing several aspects of Carver’s prolific research. Specifically, it focuses on his work in improving soil nutrition by re-introducing legumes as part of crop rotation. It highlights recent discoveries in this area as well as their importance when considering global challenges in modern agriculture and food security related to climate change.

Carver’s contribution to the adoption of legumes and soil regeneration

Carver published his own research in a series of bulletins, currently accessible at the Biodiversity Heritage Library (https://www.biodiversitylibrary.org/). Carver worked on peanuts, plums and sweet potatoes, among other plants, and he introduced cowpeas, sweet peas and soybeans as cash crops. He invented hundreds of food substitutes and derivatives, such as metal polish, paper and peanut oil, and drove 40 years of mycological research.

Most of Carver’s published work concerned finding sustainable solutions to the depletion in soil nutrition that had been caused by years of cotton growing and exploitation in southern Alabama. In one of his first bulletins (number 6, April 1905), he wrote about the importance of letting the soil rest, the fertilising value of legumes and the benefits of crop rotation[3]. He understood that, unless the farmer was able to maximise the yield and uses of alternative crops, his recommendations and discoveries would not be adopted. His experiments thrived to realistically mimic the needs and possibilities of the smallholder. For example, he used one set of horse equipment for ploughing the soils and delved extensively into the economics, calculating the cost of seeds, of preparing the soil and of the fertilisers as well as considering the price for which the planted crop would be sold.

Carver was a firm advocate of the use of legumes in crop rotation and experimented to identify the best adapted (and more profitable) species to grow successfully in the sandy soils found in Alabama. In bulletin 6 (‘How to build up worn out soils’[3]), he recommended growing vetch (*Vicia sativa*) to improve soil quality and yield in staple and cash crops, such as cotton. He also carried out experiments with clovers, peanuts as well as other legumes and recorded the benefits of inoculation with nitrogen-fixing bacteria. In bulletin 25, he experimented with alfalfa, noting that its drought-resistant characteristics made it especially good to grow in southern Alabama[4]. Carver recorded the output, in milk gallons, of cows grazed with cultivated alfalfa and gave specific instructions on how to manage the soil, when to cut and when to graze. He called the alfalfa “the king plant” for its capacity to fertilise the soil and hoped “that every farmer will plan now to put in at least a small acreage of this wonderful plant”[4]. He strongly recommended waiting three or four years after planting before grazing, indicating: “Do not make this mistake and blame something else for your failure”. In bulletin 42 (titled ‘How to build up and maintain the virgin fertility of our soils’), Carver described peas, clovers, alfalfas and soybeans as “nitrogen gatherers (soil builders)” and indicated the need to inoculate with “the little organisms, (bacteria) which cause small swellings on the roots (nodules) which contain the bacteria that enable the plant to get its nitrogen from the air”[5].

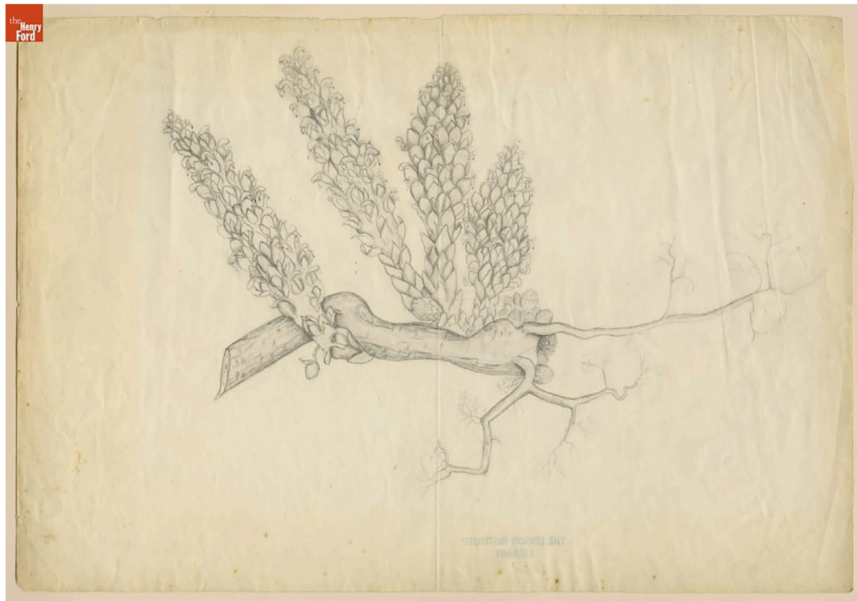
Symbiotic nitrogen fixation, a product of the association of legume roots with nitrogen-fixing bacteria, contributes to at least 70 million tons of fixed-soil nitrogen per year and accounts for between 45% and 65% of the nitrogen used in agriculture[6]. Due to its importance, the cellular and molecular processes underpinning nitrogen fixation have been a focus of attention, leading to more than a thousand research articles in the past two decades[7]. Exciting progress has been made on the chemical signalling events that precede symbiotic infection and coordinate root symbiotic association and the plant physiological status, on the plant response to infection with different types of bacteria and on the genetic determinants involved in nodule formation and regulation[8]. A recent review celebrated 20 years of discoveries in symbiotic nitrogen fixation, highlighting the key genetic components identified in legume species to be required for a successful symbiosis[7]. Despite progress, much remains to be learnt, especially on the interactions between the diverse microbial soil communities and the impact of climate change and soil conditions in legume–rhizobia symbiosis. Temperature, pH, salinity and the amount of nitrogen in the soil affect the establishment of the nitrogen-fixing symbiosis[9–11]. Carver recognised the importance of these variables and, in his bulletin 25, offered a detailed account of changes in temperature and rainfall in Macon County, Alabama, throughout a twelve-year period (1900–1912), along with recommendations on soil preparation and the adaptability of different crops to the differences in soil conditions[4]. During the four years (1912–1915) of growing alfalfa, Carver recorded the yield in pounds (lbs) of green hay and the rainfall in the collection months (bulletin 29[12]). He found that, on average, yield in a wet year was double the yield obtained in dry years, suggesting strong correlations between yield and rainfall. This is not surprising, as changes in water potential, especially periods of drought, have been shown to affect nitrogen fixation significantly, and can limit legume growth and yield[13]. A recent study in the model legumes *Medicago truncatula* and *Lotus japonicus* found that drought modifies global gene expression in root nodules but also affects the nitrogenase activity and molecular functions in the rhizobia[14]. Breeding and selection of stress-tolerant cultivars and rhizobia strains are strategies proposed (and sometimes successfully used) in overcoming changes in climatic conditions[11,15], but more needs to be done in this area.

The benefits of legumes in crop rotation and intercropping (introduced by Carver) are fully accepted by smallholder farmers and green growers.

CellPress

Diversified rotations provide higher yields for both winter and spring cereals compared with monoculture, and this is maintained under drought and high-temperature climate[16]. A study, centred in Ghana, determined that crop rotation (maize and soybean planted in consecutive seasons) increased maize yields by 41% and 49% after the fourth season[17]. The authors calculated the cost-to-benefit ratio associated with this practice and concluded that it remains profitable. In spite of this, only 60% of farmers that participated in the trials adopted this strategy more permanently. One of the reasons behind the lack of farmer engagement in this practice is that benefits are variable and not immediate. On the other hand, large-scale farm operators often prefer fertiliser mixtures over intercropping as they are pressured to provide the market with a single, standardised product. In addition, there is a need to develop suitable mechanical equipment to prepare and harvest fields planted with diverse crops[18]. The influence of crop rotation on soil microbial communities and nutrient (P and N) cycling remains under investigation, but the evidence indicates the importance of selecting the right crop-species combination according to the agro-ecosystem[19].

Through reading Carver's published research, it becomes clear that his aim is to help farmers in identifying the problems of "when, with what and how shall I fertilize my crops in such a manner as to produce the maximum yield and do it with the least financial expense and the least injury to the soil" (bulletin 42[5]). He listed the elements and water requirements to grow various crops and gave specific instructions to "make your own fertilizer on the farm". He proposed the use of plant residues and manure as sources of nutrients and, indeed, recent research estimates that non-symbiotic nitrogen fixation (associated with decomposing plant residues, decomposable particulate organic matter and bacteria living in the guts of termites and other animals) contributes to ~5–30 kg N ha^{-1} $year^{-1}$ (see[20]). Carver provided indication on the composition of different animal manure and listed the amount of nitrogen, phosphorus and potassium required for each crop. He warned of the dangers of overheating and overuse of the compost, recommending the use of legumes as natural fertilisers. Carver's research goes beyond legumes, and his scientific discoveries and methods, as indicated in the next section, ranged within and outside the areas of plant biology, botany and agriculture.



George Washington Carver's drawing of *Yucca gloriosa* (1937–1943): Image from the Collections of The Henry Ford, used with permission.

Carver's legacy beyond legumes and agriculture

Carver's best-known scientific achievements are in agriculture and the adoption of legumes and crop rotation, but his work crossed multiple disciplines. Many recognise him as a pioneer in a movement later known as chemurgy, which is a branch of chemistry dedicated to the production of industrial products from agricultural materials. He used food and crop leftovers to make ink, oil, stains and flours. He discovered 300 uses for peanuts, including to make metal polish, paper and oil (with alleged healing properties for polio), as well as adding another 100 uses for sweet potatoes, including to make molasses, postage stamp glue, flour, vinegar and synthetic rubber. Some of his inventions (such as sweet potato flour[21]) became substitutes for products unavailable during the Second World War, while others, such as the use of soy in non-dairy cheeses, were the first generation of products sold in supermarkets today. Carver only patented three of his inventions, including one for the "Process of Producing Paints and Stains" patented in the US on June 14, 1927[22]. When asked why he had not patented more, he said, "if I did it would take so much time, I would get nothing else done. But mainly I don't want my discoveries to benefit specific favoured persons"[1,22].

Carver's bulletins were not only disseminating his research findings but also contained household tips and recipes to popularise the use of alternative cash crops[23]. One of his bulletins is dedicated to the sweet potato, describing how to plant it, fertilise it and control diseases, as well as 32 ways of preparing it for consumption (boiled, baked, fried, chips, in pies, glacé, broiled, stuffed and so on), for curing and for canning[23]. He did the same for cowpeas, tomatoes and peanuts. He believed that, to engage farmers in cultivating alternative crops to cotton, it was essential to identify how to use these and how to maximise the surplus. Carver drafted a Jesup Wagon, which was used as a means of reaching the more rural areas, delivering instructions to promote the adoption of the newly developed agricultural methods and educating the farmers.

Carver was also a successful artist, a talent that he had developed since childhood from the careful observation of nature. His botanical illustrations (which exceed 71 pictures) would inspire the article titled 'Black Leonardo' in *Time* magazine in 1941[24]. Most of his drawings and paintings depicted plants or plant structures. He believed in painting and careful observation as methods to address experimental work in plants. In his 1897 article 'Progressive nature studies'[25] he encouraged teachers to provide each student with a slip of plain white or manila paper so that they could make sketches. Carver's personal artistic statement was wearing a flower in his lapel, on public appearances. Unfortunately, most of Carver's paintings were destroyed in a fire. Few survived, including his famous 'Yucca and Cactus', which was displayed at the Chicago World's Columbian Exposition of 1893 (receiving an honourable mention), and a drawing of a yucca currently accessible at the Henry Ford Collection.

Carver's main legacy remains linked to his work using plants but is not restricted to improving soil nutrition and plant growth. His discoveries to optimise plant uses and extract chemicals from leftovers as well as his contributions in raising plant awareness through his paintings and outreach/educational involvements are all part of his legacy. In an era of accelerated global warming due to the impacts of climate change, Carver's research on legumes, soils and other plant species becomes of high relevance[26,27]. Carver focused on empowering the farmer to be self-sufficient, prudent and to listen to nature, which will be an essential attitude to combat future food security issues. Carver's perseverance and success, despite the difficulties he faced, have become a powerful message and a symbol for generations of researchers of diverse backgrounds claiming their place as leaders of the scientific community today.

Final remarks from the author

I am a plant scientist, working on the discipline boundaries between cell biology, biochemistry and physical sciences. I am a Cuban-Spanish national and proud of my multiracial African lineage. I studied chemistry in Cuba as well as Spain and did my postgrad in plant biology and biochemistry. I visited many countries and took long-term research positions in the US and the UK. I must confess my ignorance, when first writing this text, concerning the work of great African Americans such as George Washington Carver. This was at the onset of the 'Black Lives Matter' movement (the biggest antiracism and human rights global network), which drove my motivation to engage with this task. Throughout the past 30 years studying science, 20 of these delivering plant research, I have come across the work of R. Franklin, B. McClintock, the Curies, Watson and Crick, Mendel, Darwin, Turing, J. Goodall, Einstein, Newton, Pauli, Pasteur and Fleming, to cite just a few, but when asked I struggle to recall the name of a single non-white plant researcher from the past century. In fact, George Washington Carver, together with the Jamaican herbalist Marie Seacole and the research chemist Percy Julian, is one of the most famous Black figures in plant research (as I soon discovered on Wikipedia). He was considered a pioneer by inventors and men of stature, such as Henry Ford and President Roosevelt. The contributions that Carver made to society, research and the economy are too many to be fairly presented in this short profile. In spite of this, and after what I consider a very international and interdisciplinary education and research background, the name George Washington Carver felt distant and indistinguishable. I am a university Associate Professor in Plant Science and an advocate for equality, diversity and inclusion. I teach plant sciences, legume symbiosis and how to build up nitrogen in soils, but Carver does not figure in my teaching curriculum because until now I was unaware of his work. If we aim to benefit from inclusive research and education, we must engage and empower diverse minorities by teaching the contributions of our multiracial scientific community. There is work to be done in decolonising the curriculum in STEM subjects and there is appetite for change (I hope). I am grateful to my funders, the UKRI Future Leaders Fellowship (MR/T04263X/1), for allowing me to focus on research and for considering work in equality, diversity and inclusion important and necessary in UK education and research, as well as my student Besiana Sinanaj for providing feedback on the first draft of this article. We are seeing George Washington Carver (and other inspiring Black leaders and pioneers) pictured more often in the media, in educational books and even in my daughter's 'Little Scientist' jigsaw. Carver's work remains relevant today in terms of plant biology, food security and sustainable agriculture in a warming world. His contributions to plant sciences and to the design of new products from agricultural surplus and waste are examples of success in applying interdisciplinary research. Society is beginning to appreciate the value of diversity in the widest sense and giving a voice to plant scientists (of diverse racial, ethnic, sexual orientation and personal backgrounds) working on the search for solutions to pressing issues, such as the impact of climate change on crop yield, and researching how to reduce our carbon footprint. It will take at least a generation for these changes in behaviour to be noticed and I would be proud and grateful if this article contributes, in any form or shape, to this revolution.

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My word

Building better theories

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Science is made of ideas and data, theory and observation. Theories can tell us which data to collect, summarise masses of observations, and explore the space of potential explanations. Some theories, the ones that describe mechanisms, can even turn straw into gold — transforming data into explanations of the world around us. Given the central importance of theory, there are good reasons to worry about the lack of ideas in biology[1], and the 'theory crisis' in the cognitive and behavioural sciences[2,3]. It has been argued that this lack of 'novel ideas' is slowing scientific progress[4], but what can be done?

In the long term, we need to look closely at how scientists are trained. Typically, students are taught a great deal about how to collect data and next to nothing about how to formulate and evaluate theory. We force feed techniques and statistics, but, like parental prudes, leave the kids to work out for themselves where theories come from. In the medium term, there is no shortage of detailed, technical advice for those with the freedom and inclination to make radical changes to their science — to get into formal modelling or interdisciplinary collaboration[5–7] — but even these changes can leave the core theoretical problems unresolved[8]. In the short term, we can all up our theoretical game by thinking a little harder about what theories are for, how they should be constructed, and which tests are worth the effort.

In this My Word, we offer a checklist of seven questions we find useful when formulating and testing our own theories, and when thinking through the work of others in our research fields. Theory has several functions[9] but, like many scientists, we want our work to contribute to explanation. Therefore, whenever we say 'theory' we mean mechanistic theory — the kind that has the potential to be explanatory[10]. Otherwise, we are broad-minded — a mechanistic theory may be labelled as such or as a 'model'; it can be formal, for example computational/mathematical, or informal, for example graphical/narrative. Without naming and shaming, we use examples from our own fields of research — social cognition, memory, perception, and action — areas where cognitive science meets neuroscience and evolution.

What is the target?

A theory needs a target or 'explanandum' — a phenomenon that exists or occurs in the natural world that the theory is designed to explain. There are very few constraints on the size of the target — classics include magnetism, oxidation, fermentation, and lava flow — but, whatever the size or aspect of the natural world, the target should show some signs of unity, of being a 'thing'. Say you want to explain imitation. If you define imitation loosely, to encompass all sorts of vaguely social learning, you are unlikely to come up with a successful theory because the cases are probably not produced by the same causal structure. It is unlikely that the same psychological or neurological mechanism enables snails to find food by following the slime trails of other snails and enables people to learn calculus by reading textbooks. On the other hand, if you define imitation tightly — for example, as copying behavioural topography, the way that parts of the body move relative to one another — there is a decent chance all cases are due to the same causal structure; that one mechanism allows imitation of scowls, arabesques and Fosbury Flops[11].

Obviously, the more you know about your target the better, and plenty of important research aims to characterise the target rather than to test theory. What are the triggers, modulators, and inhibitors? What happens when the system is damaged or operating under unusual conditions? How does the system function at different points in development and across species? Not-so-obviously, it is important to keep all this information in mind when formulating or assessing a theory. If a theory works for deliberate but not automatic imitation, or for imitation in primates but not in birds,