Evolutionary origins of plant/bacteria symbiosis

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Equipped for barren soils: Dimorphandra wilsonii Riz. enters into symbiosis with bacteria of the genus Bradyrhizobium, which provide the plant with nitrogen and receive other nutrients in return. Dimorphandra wilsonii is a tree species from the Fabaceae (legume) family and arises predominantly in low-nutrient tropical savannas. Credit: Marcia Fonseca, Lina Rivera, private

The symbiosis between some plant species and nitrogen-fixing nodule bacteria is one of the most relevant cooperative relationships in the world. It shapes our global vegetation and, not least, the global nitrogen and carbon cycle. The foundations for this process were probably laid in just one evolutionary event around 100 million years ago. This was recently discovered by an international research team including scientists from the Max Planck Institute for Biogeochemistry in Jena, Germany. The researchers also identified species that have a genetic predisposition for this symbiosis but never developed it. These plants could help with research on this symbiosis, and on how it could be crossbred into other species.

Some plants simply have the advantage over others. With the help of bacteria, they can utilise atmospheric nitrogen from the air, which they urgently require for their growth but is often not sufficiently available in a usable chemical form in the soil. It would be a dream come true for agriculture if not only legumes like lentils, peas and beans, but also wheat, rice and corn could cooperate with bacteria and become independent of nitrogen fertilisation as a result. The symbiosis between plants and bacteria also plays an important role in biogeochemical cycles: It helps plants to colonise barren soils and has a crucial influence on how ecosystems react to the rising carbon dioxide levels in the air. Due to the increased carbon-dioxide concentration in the air plants have the potential to grow faster and thus reduce the further increase in carbon dioxide levels and alleviate climate change. However, to grow faster plants will also need more nitrogen. Up to now, it was not even known when and how plants acquired the capacity for the nitrogen-fixing symbiosis.

A database of plant characteristics helps with the analysis

It is now clear that in all probability the entire process started 100 million years ago with a single evolutionary event. Through one or more mutations, a plant developed a predisposition for this symbiosis which was then altered and refined in different ways. "The predisposition appears to have neither a clear benefit nor drawback for the plant, as it was conserved in some species and was quickly lost again in others," says Jens Kattge from the Max Planck Institute for Biogeochemistry explaining the results. However, the nitrogen-fixing symbiosis only developed if the predisposition was there.

For their analyses, the researchers created the biggest database to date of all plant species that can form a symbiosis with nodule bacteria. "Around one-third of the data originate from our TRY database, which now catalogues the characteristics of over 90,000 plant species," explains Jens Kattge. "We are interested in the plant characteristics, above all in superior ecological aspects, specifically the question as to how functional plant characteristics like the capacity for nitrogen-fixing influence biogeochemical cycles – from the ecosystem to global level," says Kattge. The scientists have now reconstructed the evolution of the nitrogen fixing symbiosis using the data and a phylogenetic tree of the angiosperms. To do this they applied different mathematical models that trawl backwards through evolution starting from today's status quo.

Predisposition is highly unlikely to emerge

The models calculated that the predisposition clearly arose on a single occasion alone. "The development of a symbiosis like this with the nitrogen-fixing bacteria is extremely complex and only offers a benefit in its complete state," says biologist Jens Kattge. Numerous metabolic paths have to be reprogrammed and coordinated between the symbiotic partners. "The fact that something so complex arises is highly unlikely, but not impossible over the very long course of evolution."

Today, thousands of plant species cooperate in different ways with the nodule bacteria. Many others have the predisposition but have never formed a symbiotic relationship. "It is not yet known precisely which genes are mutated," admits Kattge. Up to now, based on genetic analysis, it has not been possible to establish which plants have already taken the first step towards the most important symbiosis and which have not.

However, using the mathematical models it is possible to calculate the probability with which a plant species will feature among the predisposed plants or not. A few surprises emerged here. Representatives from very different plant families, like the mimosa, carob and hemp families, are very likely equipped for forming a symbiotic relationship with nitrogen-fixing bacteria.

Symbiosis could easily be triggered in predisposed plants

Through the comparison of the different predisposed plants it was finally possible to track down the genes and metabolic paths responsible for symbiosis. Because the plants with a predisposition belong to different species, they should differ from each other more genetically than plants from closely related species. Therefore, the predisposition, which always remains the same, should be relatively easy to find in their genomes.

The probability that the symbiotic machinery could be started through breeding is highest in the predisposed plants. These include, for example, the hornbeam (Carpinus sp.), an important source of wood, and bitter bean (Parkia speciosa), a food plant popular in Asia. But there is a bit of bad news for native plant breeders: it is very likely that the important cereal species such as wheat, rye, barley and corn are not among the plants predisposed to this symbiosis. Until the exact mechanism of the symbiosis has been decoded, it will be difficult to transfer the capacity for this symbiosis to these plants through breeding.

The scientists at the Max Planck Institute for Biogeochemistry in Jena are not particularly interested in enabling plants to fix nitrogen with the help of nodule bacteria. Instead, they want to use the database of nitrogen-fixing plants to gain a better understanding of the global nitrogen cycle and how it is being transformed as a result of climate change. This should help to improve earth system models so that they can better forecast the influence of vegetation on the atmospheric carbon dioxide concentration and, thus also, predict the future climate with greater accuracy than can be achieved using the current models.

More information: Gijsbert D.A. Werner, William K. Cornwell, Janet I. Sprent, Jens Kattge und E. Toby Kiers. "A single evolutionary innovation drives the deep evolution of symbiotic N2 fixation in angiosperms." *Nature communications*, 10 June 2014; DOI: 10.1038/ncomms5087

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