Research Article

Similarities in the evolution of plants and cars

Samantha Hartzell¹,2, Mark Bartlett¹,3, Jun Yin¹,2, Amilcare Porporato¹,2*

¹ Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, United States of America, ² Princeton Environmental Institute, Princeton University, Princeton, NJ, United States of America, ³ Department of Civil and Environmental Engineering, Duke University, Durham, NC, United States of America

* aporpora@princeton.edu

Abstract

While one system is animate and the other inanimate, both plants and cars are powered by a highly successful process which has evolved in a changing environment. Each process (the photosynthetic pathway and the car engine, respectively) originated from a basic scheme and evolved greater efficiency by adding components to the existing structure, which has remained largely unchanged. Here we present a comparative analysis of two variants on the original C3 photosynthetic pathway (C4 and CAM) and two variants on the internal combustion engine (the turbocharger and the hybrid electric vehicle). We compare the timeline of evolution, the interaction between system components, and the effects of environmental conditions on both systems. This analysis reveals striking similarities in the development of these processes, providing insight as to how complex systems—both natural and built—evolve and adapt to changing environmental conditions in a modular fashion.

Introduction

Today, plants make up the majority of living biomass on earth [1] and the automobile is by far the most popular method of passenger transport worldwide [2]. These systems, while quite different in their functions, are powered by processes which have evolved over time in a remarkably similar fashion. Both originated from a basic, highly successful scheme and improved by adding components in a process of modular evolution. Designers of cars limited by oxygen availability developed the turbocharger [3], which functions similarly to the C4 “carbon pump” by concentrating a limiting reactant to improve efficiency [4]. As demand for fuel and water use efficiency increased, designers introduced the energy storage system of the Hybrid Electric Vehicle (HEV) to address inefficiencies caused by variable power demand [5], while plants evolved the Crassulacean Acid Metabolism (CAM) carbon storage system to reduce inefficiencies caused by diurnal variability in light and atmospheric humidity [4].

The basic photosynthetic pathway uses light energy to transform carbon dioxide into three-carbon sugars which are used to power plant processes and build tissue. This is accomplished through a complex series of processes involving the light reactions, which use light energy to break up water into oxygen and protons (fuel), and the Calvin cycle, which fixes carbon dioxide into sugar (energy). The C3 pathway, so-called because of the three-carbon sugar it produces, was the first photosynthetic pathway to evolve in modern terrestrial plants.
to the endosymbiotic theory, this pathway developed in eukaryotes around 1 Ga ago when photosynthetic cyanobacteria were first incorporated into algae as chloroplasts. This development was then carried over into terrestrial plants [6]. The basic C3 pathway can be compared to the modern Otto cycle internal combustion engine (ICE), which was patented by Nikolaus Otto in 1876. Like the revolution caused by the incorporation of photosynthetic bacteria into algae, this gasoline engine was quickly incorporated into the first automobiles (see Fig 1 for a brief evolutionary history of both systems). Since then, many aspects of the automobile design have changed, but the main agent of propulsion, the ICE, has remained remarkably consistent [7], as has the chloroplast in plants [8, 9].

Both the Otto cycle and the C3 photosynthetic pathway have limited efficiency under typical operating conditions. The internal combustion engine works by combusting fuel with an oxidizer (air). The power produced is limited, among other factors, by the amount of air taken into the engine. This is characterized by the volumetric efficiency, i.e., the ratio of the actual to the theoretical maximum amount of air which could be taken in [7]. ICEs also experience a large decrease in fuel efficiency under variable traveling speed (particularly stop-and-go traffic), as the engine is constantly running and the braking process dissipates kinetic energy. In the C3 photosynthetic pathway, carbon dioxide diffuses into the leaf and reacts with ribulose-1,5-bisphosphate (RuBP) to produce sugars, which are ultimately used to form carbohydrates (see Fig 2). Efficiency is strongly impacted by photorespiration, a process by which RuBP reacts with oxygen, rather than carbon dioxide. Under the modern atmospheric composition, the high concentration of oxygen relative to carbon dioxide leads to significant photorespiration, reducing the overall efficiency of C3 plants by about one-third [11]. Plant efficiency is also limited by considerations of water availability. Water use efficiency, i.e., the ratio of carbon assimilated to water vapor lost, is a key determinant of plant performance in water-limited conditions [12, 13]. Plant water use efficiency decreases strongly when certain atmospheric conditions (high temperatures and low humidity) cause a high evaporative demand.

**Materials and methods**

**Turbocharged vs. conventional ICEs**

In order to illustrate the advantages of turbocharged and supercharged engines in environments with low substrate (oxygen) concentration, we compared the power output of these engines with conventional ICEs under decreasing oxygen concentration caused by increasing altitude in airplanes. In the case of the supercharged engine, data were obtained on power output with altitude for the Merlin III aircraft during World War II [14]. Power output for conventional ICEs is plotted using an estimate of 3% power loss per thousand foot altitude gain [15].

**C4 vs. C3 photosynthesis**

We compared the yield of “supercharged” C4 crops (corn and sorghum) with conventional C3 crops (soybeans and wheat) under varying substrate (CO₂) concentration. Data for each of the four crops was obtained from a synthesis presented by Long et al. [16] and represents those grown at ambient CO₂ levels and at elevated CO₂ levels in chamber experiments. These included 155 measures of soybeans, 211 of wheat, and 14 of corn and sorghum. Solid lines represent a least-squares fit to the data.

**Hybrid electric vehicles vs. ICEs**

In order to show how the advantages of hybrid cars increase with variability in driving speed, we analyzed data on gas mileage in model year 2007 vehicles subject to the Environmental
The Protection Agency (EPA)'s Federal Test Procedure (FTP) cycles. Variance in speed was calculated for both city and highway cycles and mileage information was obtained from model year 2007 vehicles, which have hybrid and conventional counterparts with the same engine: the Toyota Camry, Ford Escape, Nissan Altima, GMC Sierra, and Mercury Mariner. Mileage data

Fig 1. Comparative evolution of plants and cars. (a) In 1885, Karl Benz was among the automobile's first producers, and in 1908, the Ford Motor Company pioneered the first mass produced automobile, the Model T [5]. The turbocharger gained popularity during World War II, when it was used in military aircraft, which had to cope with low-pressure, high-altitude air [3], and the first turbocharged passenger car, the Chevrolet Corvair Monza, debuted in 1962 [10]. Serious interest in hybrid technology arose in the 1960s when it was recognized as a means for harnessing variability in driving conditions to lower fuel use and emissions, and the Toyota Prius was introduced in 1997 as the first mass produced hybrid car [5]. (b) The first C3 plants developed around 1 Ga ago as aquatic lifeforms [6]. CAM photosynthesis evolved during the Paleozoic era and likely experienced a significant expansion in terrestrial plants in the Cenozoic era, which was accompanied by increasing seasonality of water availability [4]. C4 photosynthesis is thought to have first evolved in the mid-Tertiary period and experienced a large increase in the late Miocene, 4-7 Ma, which brought decreasing CO$_2$ levels [4].

https://doi.org/10.1371/journal.pone.0198044.g001
was obtained from U.S. Department of Energy and U.S. EPA [17]. Data on speed variance were extracted from city and highway FTP cycles [18].

**CAM vs. C3 crops**

To demonstrate how the advantages of CAM photosynthesis depend on variability in transpiration demand, we compared the water use efficiency for C3 and CAM plants with increasing diurnal variability of the vapor pressure deficit. The results were obtained using the Photo3 model [19], which is based on the the Farquhar et al. C3 model [20] and a recently introduced CAM model [21, 22], for one representative species of each photosynthetic type: winter wheat (*Triticum aestivum*) for C3 and prickly pear (*Opuntia ficus-indica*) for CAM. The model was run with a soil moisture of 0.56, soil type of loamy sand, carbon dioxide concentration of 400 ppm; daytime temperature of 303.15 K, solar radiation of 500 W/m², and vapor pressure deficit of 2.89 kPa; and a nighttime temperature of 288.15 K, solar radiation of 0 W/m², and varying nocturnal vapor pressure deficit. Water use efficiency (WUE) is given as a function of decreasing nocturnal vapor pressure deficit, with daytime vapor pressure deficit held constant.
Results

Evolution of the substrate concentration mechanism

Over time, both car engines and plant photosynthetic pathways have added components to improve efficiency while leaving the original structures (the ICE and the C3 Calvin cycle) intact. The turbocharger and the C4 carbon pump are added components, which improve performance (engine power output or photosynthetic yield) when low levels of oxygen and carbon dioxide, respectively, limit the efficiency of the core process. The turbocharger adds a turbine and an air compressor to the original ICE. The turbine, driven by the engine’s exhaust gases, powers a compressor which forces more air into the combustion chamber, increasing the available concentration of oxygen (see Fig 2). This improves the volumetric efficiency of the engine and allows a greater power output with less fuel use. Similarly, the C4 photosynthetic pump adds a second carbon fixation process which raises the CO$_2$ concentration in the chloroplasts by an order of magnitude. The first pathway functions by carboxylating phosphoenolpyruvate (PEP) to produce a 4-carbon sugar (hence the term C4). The 4-carbon sugar then enters the bundle sheath cell where it is decarboxylated and fixed by RuBisCO in the Calvin cycle (see Fig 2 for a comparison of car and plant components). Because C4 photosynthesis concentrates the CO$_2$ at the site of the Calvin cycle, it is able to effectively eliminate photorespiration. This allows the plant to assimilate more carbon with less stomatal opening and water loss.

The turbocharger and the C4 carbon pump developed under limiting oxygen and carbon dioxide conditions, respectively, and both show the greatest advantages over their traditional counterparts in such conditions. Fig 3a compares the power output of the Merlin III, a supercharged jet from WWII, to that of a conventional, non-supercharged airplane, as oxygen pressure changes at altitude. The Merlin III outperforms its conventional counterpart by over 100% at altitudes over two thousand feet, where the oxygen pressure is one-twentieth of that at sea level, but it is limited at lower altitudes due to the power required to run the supercharger. Today, highly developed turbochargers enable decreased fuel consumption and emissions even at sea level and increasingly stringent emissions regulations have caused an increase in the popularity of turbochargers in passenger cars and especially in trucks. Similarly, C4 plants outperform their C3 counterparts most strongly under conditions of low CO$_2$. Because of decreased photorespiration they are able to assimilate more carbon and are 2-3 times more water efficient[11]. At the same time, C4 photosynthesis comes with a slight energetic drawback because of the cost of the additional chemical reaction. Thus, the advantages of C4 plants increase strongly at low carbon dioxide levels, and drop off at high CO$_2$ levels, where these plants require more solar radiation to assimilate the same amount of carbon (see Fig 3b).

Evolution of the energy storage mechanism

In a separate strategy, cars and plants both developed energy storage mechanisms, i.e., HEV technology and CAM photosynthesis, which increase efficiency in conditions of high environmental variability. HEVs add a battery and an electric motor to the existing internal combustion engine in order to enable “regenerative braking”—when the brakes are employed, some of the resulting kinetic energy is turned into electricity and stored in the battery. This energy can later be used by the electric motor to assist the internal combustion engine in a dual motor hybrid drivetrain configuration[23–25]. Similarly, the CAM photosynthetic pathway accumulates 'fuel’ in the form of carbon in the enlarged plant vacuole ‘battery.’ In CAM photosynthesis, stomata open during the night, when transpiration drivers are low, and fix atmospheric CO$_2$ as a 4-carbon sugar, typically malic acid, which is stored in the cell vacuole. The malic
Acid then is decarboxylated during the day and fixed via RuBisCO in the C3 Calvin cycle, which requires light energy (see Fig 2).

Both the HEV and the CAM plant thrive under conditions where efficiency (either fuel efficiency or water use efficiency) is paramount and variability is high. The rise of the hybrid car depended on limiting fuel resources and high demand to improve automobile efficiency. This technology can provide improvements in efficiency up to 34% under stop-start and hilly driving conditions when power demand is variable [26]. At the same time, it introduces the costs of the second power system, the battery, and the more complex control system [24, 27, 28]. Due to this tradeoff, hybrid cars show much better performance than their conventional counterparts under conditions of high variability in driving speed, while they show similar performance under conditions of low variability (see Fig 3c). Likewise, the CAM pathway is favored in terrestrial environments limited by high costs of daytime stomatal opening due to large water losses, including many arid and semi-arid regions of the world. Because CAM allows the stomata to open at night, when there is a much lower driving force for water loss, CAM water use efficiency is up to six times higher than C3 water use efficiency under typical environmental conditions. Since there is an additional chemical reaction involved, CAM

Fig 3. Additional components allow more newly developed photosynthetic systems and car engines to outperform conventional ones under specific conditions. (a) Supercharged engines outperform conventional ICEs with increasing altitude (decreasing O2 concentration). (b) Likewise, “supercharged” C4 crops (corn and sorghum combined data) outperform “conventional” C3 crops (soybeans (o) and wheat (x)) with decreasing CO2 concentration. (c) Hybrid cars strongly outperform their traditional counterparts under conditions of high variability in driving speed, while they perform similarly under conditions of low variability. (d) In a similar fashion, CAM plants strongly outperform their C3 counterparts in conditions of high variability in vapor pressure deficit, while they are less efficient in the absence of variability.

https://doi.org/10.1371/journal.pone.0198044.g003
comes with an energetic drawback on the order of 10-20% compared with C3 plants, although this requirement varies depending on what percentage of CO$_2$ is taken up at night [29, 30]. Like hybrid cars, which strongly outperform their traditional counterparts when driving speed is highly variable, CAM plants show a major advantage over their C3 counterparts in conditions of high diurnal variability in vapor pressure deficit, a major driver of evaporative demand (see Fig 3d).

Discussion

Some of the most common modifications to the ICE have striking similarities to the more recently evolved photosynthetic pathways. CAM plants and HEVs differ in a major regard, however, in that the structure of the HEV leaves potential for a redundant power system while that of the CAM plant does not. On the one hand, the CAM plant converts the carbon stored as malic acid back into carbon dioxide before fixing it in the basic C3 Calvin cycle (see Fig 2). On the other hand, parallel hybrid cars use the stored energy in the battery to power the drive-train electrically through the motor, bypassing the engine entirely. The redundant power system in the HEV, which contains both the ICE and the electric motor, has facilitated the development of the plug-in HEV whose external source of energy comes from both gasoline and electricity [24]. As battery and other electric vehicle technology improves, these systems are becoming a viable option and are replacing the original ICE entirely in some cars, i.e. battery electric vehicles [31]. It would appear that when the means have developed to utilize an entirely new energy source, the stage has been set for the underlying scheme to be usurped by a new one. Indeed, this phenomenon has also been observed in the plant world. As parasitic plants developed the ability to gain carbon from a photosynthetic host, many underwent massive changes in the chloroplast genome leading to loss of photosynthetic function [8]. Parasitic plants, like battery electric vehicles, remain a striking exception to the rule of a highly conserved central component.

The parallels in the evolution of these very different energy production systems provide interesting insight as to how such complex systems are modified over time. In response to moderate environmental pressures, both cars and plants have evolved secondary components to increase the efficiency of the core energy-generating mechanism, while the core mechanism itself remained largely unchanged. Both systems exhibit a high degree of modularity, whereby functional units develop, which are relatively distinct from the surrounding structure [32]. While such modular systems tend to be non-optimal, they are believed to persist because they provide stability and robustness, and show higher adaptability and survival rates under changing environments [32–35]. In both cars and plants, the unchanging central module may lend each system a certain robustness, while the development of auxiliary modules has allowed each system to adapt to changing goals presented by novel environments. The fact that such similar responses can be found in both animate and inanimate systems suggest that a universal mechanism or 'design principle' may be at play, e.g. Hartwell et al.; Variano et al.; Bejan et al. [33, 36, 37].

We are likely to observe these dynamics at work in the near future, as, Ironically, the pressures of climate change may drive the evolution of plants and cars in very different directions. Climate change is expected to affect plant function through increased levels of carbon dioxide, temperature, and, in many areas, aridity. At a first glance, these changes might be expected to increase the performance of CAM and decrease the performance of C4 relative to C3 photosynthesis [38–41]. However, these outcomes are far from certain and depend on a complex interplay of other factors [42, 43]. In any case, the pressures of anthropogenic climate change are relatively modest compared with historical changes to which the photosynthetic pathway
has already been subjected. Considering that photosynthesis has already withstood the test of time, the existing photosynthetic pathways may be expected to adapt to current changes without major evolution. In cars, the story may be different. Modular evolution has historically allowed innovation in automotive technology to adjust quickly to changing goals, yielding turbocharged and hybrid EVs. Yet the prospect of climate change is dramatically increasing pressure to lower carbon dioxide emissions, and perhaps even reduce them to zero. This pressure has led to the exploration of novel technologies, some of which (including battery and fuel-cell electric vehicles) replace the original ICE altogether [24, 44, 45]. Such technologies have taken more time to develop and may be considered more risky strategies in that they require massive updates to existing infrastructure and manufacturing practices. Compared with plants, which have existed on earth for millions of years, cars are a relatively young technology with interesting possibilities ahead.

**Acknowledgments**

We thank Simon Levin and two anonymous reviewers for their useful comments. This work was supported through the USDA Agricultural Research Service cooperative agreement 58-6408-3-027 and National Institute of Food and Agriculture (NIFA) grant 12110061; and National Science Foundation (NSF) grants CBET-1033467, EAR-1331846, FESD-1338694, EAR-1316258, GRFP-1106401 and the Duke WISENet Grant DGE-1068871.

**Author Contributions**

**Conceptualization:** Amilcare Porporato.

**Investigation:** Samantha Hartzell, Mark Bartlett, Jun Yin.

**Methodology:** Mark Bartlett, Jun Yin, Amilcare Porporato.

**Supervision:** Amilcare Porporato.

**Visualization:** Jun Yin.

**Writing – original draft:** Samantha Hartzell.

**Writing – review & editing:** Samantha Hartzell, Amilcare Porporato.

**References**

1. Whitman WB, Coleman DC, Wiebe WJ. Prokaryotes: The unseen majority. Proceedings of the National Academy of Sciences. 1998; 95(June):6578–6583. https://doi.org/10.1073/pnas.95.12.6578
2. Schafer A, Victor DG. The future mobility of the world population. Transportation Research Part A. 2000; 34.
3. Society of Automotive Engineers. Turbochargers and Turbocharged Engines. Warrendale, PA; 1979.
4. Keeley JE, Rundel PW. Evolution of CAM and C4 Carbon Concentrating Mechanisms. International Journal of Plant Sciences. 2003; 164(May 2003).
5. Anderson CD, Anderson J. Electric and hybrid cars: A history. Jefferson, NC: McFarland & Company; 2005.
6. Xiong J, Bauer CE. Complex evolution of photosynthesis. Annual Review of Plant Biology. 2002; 53. https://doi.org/10.1146/annurev.arplant.53.1000301.135212 PMID: 12221987
7. Cummins CLJ. Internal Fire. Lake Oswego. Oregon: Carnot Press; 1976.
8. Bungard RA. Photosynthetic evolution in parasitic plants: insight from the chloroplast genome. BioEssays. 2004; 26:235–247. https://doi.org/10.1002/bies.10405 PMID: 1498925
9. Wicke S, Schneweiss GM, DePamphilis CW, Muller KF, Quandt D. The evolution of the plastid chromosome in land plants: gene content, gene order, gene function. Plant Molecular Biology. 2011; 76:273–297. https://doi.org/10.1007/s11103-011-9762-4 PMID: 21424877
10. Rajoo S, Martinez-Botas R. Automotive Turbocharging. In: Rajoo S, editor. Research on Vehicle Technologies. Malaysia: Univision Press; 2008.
11. Ehleringer JR, Monson RK. Evolutionary and ecological aspects of photosynthetic pathway variation. Annual Review of Ecological Systems. 1993; 24. https://doi.org/10.1146/annurev.es.24.110193.002211
12. Rodriguez-Iturbe I, Porporato A. Ecohydrology of water-controlled ecosystems. Cambridge University Press; 2004.
13. Lambers H, Stuart Chapin F III, Pons TL. Plant Physiological Ecology. 2008.
14. Williams M, Stirling N. Spitfire Mk. I versus Me 109 E: A Performance Comparison; 2008.
15. Lowrie RL, editor. SME Mining Reference Handbook. SME; 2002.
16. Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR. Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations. Science. 2006; 312(June):1918–1922. https://doi.org/10.1126/science.1114722 PMID: 16809532
17. U S Department of Energy, U S Environmental Protection Agency. 2007 Fuel Economy Guide; 2007. Available from: https://www.fueleconomy.gov/feg/fe_test_schedules.shtml.
18. Hartzell S, Bartlett MS, Virgin L, Porporato A. Nonlinear dynamics of the CAM circadian rhythm in response to environmental forcing. Journal of Theoretical Biology. 2015; 368:83–94. https://doi.org/10.1016/j.jtbi.2014.12.010 PMID: 25542971
19. Ehsani M, Yimin G, Miller JM. Hybrid Electric Vehicles: Architecture and Motor Drives. Proceedings of the IEEE. 2007; 95(4):719–728. https://doi.org/10.1109/JPROC.2007.892492
20. Hartzell S, Bartlett MS. Advanced automobile engines for fuel economy, low emissions, and multifuel capability. Annual Review of Energy. 1989; 14:425–444. https://doi.org/10.1146/annurev.eg.14.110189.002233
21. Yu H, Cheli F, Castelli-Dezza F, Cao D, Wang FY. Multi-objective Optimal Sizing and Energy Management of Hybrid Energy Storage System for Electric Vehicles. IEEE Transactions on Vehicular Technology. 2018; 67(2):1027–1035. https://doi.org/10.1109/tvt.2017.2778314
22. Winter K, Smith JAC, editors. Crassulacean acid metabolism: Biochemistry, ecophysiology and evolution. vol. 114. Springer-Verlag Berlin Heidelberg; 1996.
23. Simms JP, Alon U, Murray AW. From molecular to modular cell biology. Nature. 1999; 399:792–798. https://doi.org/10.1038/13851
24. Howey DA. Policy: A challenging future for cars. Nature Climate Change. 2012; 2:28–29. https://doi.org/10.1038/nclimate1336
25. Lipson H, Pollack JB, Suh NP. On the Origin of Modular Variation. Evolution. 2002; 56(8):1549–1556. https://doi.org/10.1111/j.0010-0582.2002.tb01466.x PMID: 12333747
26. Hartwell LH, Hopfield JJ, Leibler S, Murray AW. From molecular to modular cell biology. Nature. 1999; 402:47–52. https://doi.org/10.1038/3501540
27. Kashtan N, Alon U. Spontaneous evolution of modularity and network motifs. Proceedings of the National Academy of Sciences. 2005; 102(39). https://doi.org/10.1073/pnas.0503810102
28. Parter M, Kashtan N, Alon U. Environmental variability and modularity of bacterial metabolic networks. BMC Evolutionary Biology. 2007; 7(169). https://doi.org/10.1186/1471-2148-7-169 PMID: 1788177
36. Variano EA, McCoy JH. Networks, Dynamics, and Modularity. Physical Review Letters. 2004; 92(18):1–4. https://doi.org/10.1103/PhysRevLett.92.188701

37. Bejan A, Lorente S. The constructal law and the evolution of design in nature. Physics of Life Reviews. 2011; 8(3):209–240. https://doi.org/10.1016/j.plrev.2011.05.010 PMID: 21683663

38. Ehleringer JR, Sage R, Flanagan L, Pearcy R. Climate change and the evolution of C4 photosynthesis. Trends in ecology & evolution. 1991; 6(3):95–99. https://doi.org/10.1016/0169-5347(91)90183-X

39. Nobel PS. Responses of some North American CAM plants to freezing temperatures and doubled CO2 concentrations: Implications of global climate change for extending cultivation. Journal of Arid Environments. 1996; 34(2):187–196. https://doi.org/10.1006/jare.1996.0100

40. Collatz GJ, Berry JA, Clark JS. Effects of climate and atmospheric CO2 partial pressure on the global distribution of C4 grasses: present, past, and future. Oecologia. 1998; 114(4):441–454. https://doi.org/10.1007/s004420050468 PMID: 28307893

41. Yang X, Cushman JC, Borland AM, Edwards EJ, Wullschleger SD, Tuskan GA, et al. A roadmap for research on crassulacean acid metabolism (CAM) to enhance sustainable food and bioenergy production in a hotter, drier world. New Phytologist. 2015; 207:491–504. https://doi.org/10.1111/nph.13393 PMID: 26153373

42. Reddy AR, Rasineni GK, SRA. The impact of global elevated CO2 concentration on photosynthesis and plant productivity. Current Science(Bangalore). 2010; 99(1):46.

43. Reich PB, Hobbie SE, Lee TD, Pastore MA. Unexpected reversal of C3 versus C4 grass response to elevated CO2 during a 20-year field experiment. Science. 2018; 360(April):317–320. https://doi.org/10.1126/science.aas9313 PMID: 29674593

44. Van Mierlo J, Maggetto G, Lataire P. Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles. Energy Conversion and Management. 2006; 47(17):2748–2760. https://doi.org/10.1016/j.enconman.2006.02.004

45. Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy. 2010; 38(1):24–29. https://doi.org/10.1016/j.enpol.2009.08.040