Ecological Reasoning in Nineteenth-Century Agricultural Science

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In the first half of the nineteenth century, agricultural science flourished in Germany, France, and Great Britain through the establishment of agricultural schools, experimental stations, and university professorships. Agricultural science was a ›practical science‹ that combined technological and natural inquiry, much like other practical sciences of the time, such as mining science and forestry science.[1] Agricultural scientists studied the physical, chemical, and botanical conditions under which crops grew, as well as the agricultural methods that allowed farmers to maintain and intensify the cultivation of crops. However, the intensification of agriculture, which went hand in hand with industrialization and population growth, created a serious environmental problem: soil depletion. In the face of a growing human population, many nineteenth-century agricultural scientists considered soil depletion as the major social and political challenge of their time. Studies of the causes of soil depletion and the possibility of maintaining soil fertility through artificial fertilization stimulated questions about the ecological relationships between plant growth, plant nutrients, soil, water, and climate. Two German scientists were particularly influential in moving agricultural studies toward environmental inquiry: the chemist Justus Liebig and the botanist Carl Fraas. The two men represented different approaches in agricultural science. While Liebig, the chemist, emphasized the application of chemical knowledge, Fraas's approach relied heavily on his knowledge of botany, plant geography, and agricultural field experiments. However, both men shared an interest in the social and political implications of agricultural science and provided insights, albeit different ones, into environmental problems. The paper examines the work of Liebig and Fraas, as well as the criticism of Liebig by his English rivals, the agricultural scientist John B. Lawes and the chemist Joseph Henry Gilbert. It shows that Liebig's and Fraas's linking of chemical, botanical and technical agricultural knowledge with contemporary socio-political

1 Practical Science is an actors' term; see Klein, Ursula: Technoscience in History, Prussia, 1750–1850, Cambridge, MA: MIT Press 2020.

problems of natural resource supply stimulated inquiry into soil fertility and other environmental conditions of crop growth.

Justus Liebig: The Chemist's Approach to Agriculture

Justus Liebig (1803–1873) is celebrated today as a great scientist who helped make chemistry a modern and exact science, while his practical activities and role as an agricultural scientist are known to only a few. At the age of seventeen, Liebig began studying chemistry at the Prussian University of Bonn with the idea of joining his father's chemical business. Soon after, the young Hessian received a travel grant from the Duke of Hesse-Darmstadt to study in Paris in exchange for information on French industry. After being appointed a professor of chemistry at the University of Giessen, Liebig maintained his contacts with the state and advised the government on technical matters. In 1824, shortly after he had become a professor, the Hessian government commissioned him to analyze the salts and brines of Salzhausen, near Kreuznach, where it wanted to build a spa. Liebig wrote in a letter that he was »too pleased to do this, since it means I become closely connected with the state«.[2] In 1827 he founded a private chemical-pharmaceutical institute, with the approval of the government, whose main purpose was to train industrial chemists. One of his successes in pharmaceutical chemistry was the isolation and purification of pharmaceutically useful alkaloids in the 1830s, in collaboration with the pharmacist Georg Franz Merck. Like many chemists of his time, he »was continually on the alert to the industrial and commercial implications of his current investigations«.[3] In 1852, he accepted an offer of a professorship at the University of Munich, where a new chemistry building was constructed for him. By this time, he was at the height of his scientific career and received numerous international academic and political honors – not least for his achievements in agricultural science.

In line with the physiocratic movement of his time, Liebig considered agriculture to be the most important of all human industries. He took his first steps toward agricultural science in the late 1820s, when the government of Hesse-Darmstadt sent him to France to study the French sugar beet industry. At that time, the cultivation of sugar beets and the production of beet sugar already had a longer history. In 1747, the Prussian chemist and apothecary Andreas Sigismund Marggraf had

2 Quoted after Brock, William H.: Justus von Liebig. The Chemical Gatekeeper, Cambridge: Cambridge University Press 1997, p. 117. Brock's biography shows impressively that Liebig systematically combined pure and applied chemistry.

3 W. H. Brock: Justus von Liebig, p. 119. Liebig had come into contact with Alexander von Humboldt during his stay in Paris. In the preface to his *Agricultural Chemistry* he thanked him at length for his support.

analyzed local beet varieties and found that they contained a kind of sugar identical to the expensive imported cane sugar. Thirty-five years later, his student Franz Carl Achard, with the support of the Prussian state, launched a major technological project to make this discovery industrially viable. After numerous experiments on the cultivation of sugar beets, he experimented with the extraction of beet sugar in the laboratory of the Royal Prussian Academy of Sciences and succeeded in isolating beet sugar in impressive quantities by 1801.[4] With financial support from the Prussian state, he built a sugar beet factory in Cunern (Silesia). During the Napoleonic Wars, the French government had also invested in the sugar beet industry, making the country less dependent on sugar imports from the West Indies. In the late 1820s, the high sugar prices in the German states prompted the Hessian government to take a look at the French advances with the help of Liebig.

Ten years later, agricultural chemistry had become Liebig's favorite practical subject. His *Organic Chemistry in its Application to Agriculture and Physiology*, published in 1840, was quickly translated into eight languages and made him a prominent agricultural expert throughout Europe.[5] Liebig revised his *Agricultural Chemistry* frequently, and over time his criticism of the existing agricultural practices became more vehement. By the time the last edition of the book appeared in 1862, he had become politically radicalized. He accused landowners and farmers of overexploiting the land and demanded that the state prevent agricultural robbery (*Raubbau*) and soil exhaustion (*Erschöpfung des Bodens*). With a growing world population, he argued, the supply of crops was essential to prevent famine and terrible wars. If soil depletion continued, he warned, »nations will be forced, for their own preservation, to tear each other apart and destroy each other in cruel battles to restore the balance«. The survivors »will see hundreds of thousands dying in the streets«, and »mothers will drag home the bodies of slain enemies, as in the Thirty Years' War, to satisfy the hunger of their children with their flesh«.[6]

Already in its first edition, Liebig's *Agricultural Chemistry* dealt in detail with plant nutrients, the physiology of plant nutrition, and the cycling of nutrients through the soil and the atmosphere. Liebig considered all these issues practically relevant for agriculture. Plant nutrition and the problem of maintaining soil fertility had long been studied in the German agricultural schools, which proliferated during the nineteenth century, reaching twenty-five by the time of Liebig's death.[7] Liebig was

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4 See U. Klein: Technoscience in History.

5 See Liebig, Justus: Die Organische Chemie in ihrer Anwendung auf Agricultur und Physiologie, Braunschweig: Vieweg 1840. For the reception of the treatise, see W. H. Brock, Justus von Liebig.

6 Liebig, Justus: Die Chemie in ihrer Anwendung auf Agricultur und Physiologie, Braunschweig: Vieweg [7]1862, p. 125–126; all translations are mine.

7 See Rossiter, Margaret W.: The Emergence of Agricultural Science. Justus Liebig and the Americans, 1840–1880, New Haven: Yale University Press 1975; Harwood Jonathan: Technology's

familiar with the teaching and experimenting carried out in these schools, especially with the agricultural school founded by Albrecht Daniel Thaer in 1806. Thaer (1752–1828) had studied medicine at the University of Göttingen and then practiced as a physician in his hometown of Celle. In 1784, he became a member of the Royal Agricultural Society of Celle, and began to carry out agricultural experiments. A few years later, he established a model farm for carrying out agricultural experiments and demonstrating advanced farming technologies, which were adopted in part from England. In his publications he argued for a scientific training of farmers, and he soon became known as an authority in agricultural science. In spring 1802, he founded an agricultural school in Celle, which organized public lectures on agricultural science, chemistry, and botany. When in the same year the Prussian statesman Karl August von Hardenberg paid Thaer a visit, he made him an offer to establish, with state support, a model farm along with an agricultural school in Prussia. Thaer accepted and soon afterwards bought an estate in Möglin, near Bad Freienwalde in the Oderbruch region. Beginning in November 1806, he taught a one-year course that combined agricultural practice with agricultural science and neighboring disciplines. The lectures took place in the morning and in winter on several afternoons, while in summer all afternoons were reserved for practical work. In August 1810, shortly after the founding of the Berlin University, Thaer was appointed an extraordinary professor of cameral science. Until 1819, he taught two courses for future state officials, a course on the management of landed estates – »rural economy in connection with the so-called cameralistic and agricultural policy« – and a course on agriculture and animal husbandry.[8] He combined these lectures with practical instructions at his estate in Möglin.

Liebig was particularly interested in Thaer's experiments on fertilization. He also scrutinized the agricultural writings of Carl Sprengel (1787–1859), Thaer's assistant at the agricultural school at Möglin. From 1829 until 1831, Sprengel was a lecturer on agricultural chemistry at the University of Göttingen, and from 1831 he taught agricultural science at the Collegium Carolinum in Braunschweig. He was the first German agricultural scientist who questioned the then common view that plants required organic compounds for growth. His studies provided important incentives for Liebig's more elaborate criticism of this traditional view.

In the early nineteenth century many chemists, naturalists, and agronomists believed that plants needed organic substances for growth and that humus contained the essential organic plant nutrients. This so-called humus theory was a major target of Liebig's criticism. »The first sources of nourishment for plants

Dilemma. Agricultural Colleges Between Science and Practice in Germany, 1860–1934, Frankfurt a.M.: Lang 2005.

8 Klemm, Volker/Meyer, Günther: Albrecht Daniel Thaer. Pionier der Landwirtschaftswissenschaften in Deutschland, Halle: Niemeyer 1968, p. 90.

come exclusively from inorganic nature«, he argued.[9] Chemical analysis proved that the most common chemical components of plant tissues were carbon, hydrogen, oxygen, and nitrogen. Hence, these elements were also the most essential plant nutrients. Their natural supply came in the form of ›carbonic acid‹ (carbon dioxide), water, and ammonia. According to Liebig, all of these compounds were present in the atmosphere. Based on the concept of photosynthesis, previously proposed by several chemists, he argued that plants absorbed carbon dioxide from the surrounding air and that the decomposition of rainwater yielded hydrogen and oxygen.[10] He also believed that the atmosphere contained ammonia, both in gaseous form and dissolved in rainwater. Ammonia, he pointed out, entered the atmosphere in gaseous form as a product of animal and plant decomposition and was subsequently dissolved in rainwater and absorbed by the roots and leaves of plants.[11] As carbon dioxide, water, and ammonia were also the last products of vegetable decomposition, a full material cycle was completed from the germination of plants to their decay and decomposition. Liebig argued that in addition to the four essential elements, plants also needed small amounts of other mineral nutrients, especially phosphorus, potassium, sodium, lime, and magnesia, which were provided by the soil.[12]

In his discussion of agricultural practices, Liebig emphasized that fertilizers were essential for the complete recycling of plant nutrients and thus for the prevention of soil depletion. Since harvesting crops disrupted the natural process of nutrient recycling, rational agriculture had to restore the nutrient cycle through artificial fertilization. »The principle of agriculture«, Liebig pointed out, »must be that the soil must be given back *in full measure* what is taken from it«.[13] The latter part of the argument became known as Liebig's ›law of minimum‹, which states that the growth of a plant is limited by the one essential mineral that is in relatively short supply.

Liebig embedded the knowledge about plant nutrients in considerations of how plants absorbed inorganic nutrients from the atmosphere, rainwater, and soil, converted them into the organic components of plant tissues, and contributed to their recycling through plant putrefaction and decay. However, the question of how to achieve proper fertilization was still a challenging practical problem. Farmers and agronomists had long experimented with fertilizers and found that different types of crops and soils required different types of fertilizer. The resulting picture was as

9 J. Liebig: Die Organische Chemie in ihrer Anwendung (1840), p. 3.

10 The concept of photosynthesis was developed mainly by Jan Ingenhausz, Jean Senebier, and Theodore de Saussure.

11 J. Liebig: Die Organische Chemie in ihrer Anwendung (1840), p. 65–66, p. 68, p. 71, p. 79.

12 See ibid., p. 85–86.

13 Ibid., p. 167 [my emphasis].

unclear as it was controversial. In the 1840s, Liebig was convinced that chemistry could solve all practical agricultural problems, thus elevating chemistry to the throne of the most useful of all sciences. By the time the last edition of *Agricultural Chemistry* appeared some twenty years later, however, he had become more skeptical.

As long as Liebig focused on the chemical components of plants and plant nutrients, he was in the safe domain of chemistry. But it was much more difficult to understand the entire process of plant nutrition, especially the role of the soil in it, and the interactions between the soil, the nutrients, and the roots of plants. In 1840, Liebig regarded chemistry as a science that could solve all plant physiological problems. He then believed that the soil was analogous to a chemical vessel containing plant nutrients, and that the plant was best understood as a chemical factory that transformed the inorganic nutrients into the organic components of plant tissues, with the roots and leaves of plants functioning as the factory's entrance doors. In this view, the soil was a passive deliverer of plant nutrients, and a chemical aid to their retention, whereas its texture and physical properties could be ignored. Likewise, the atmosphere was restricted to its role as a mere container of water, carbon dioxide, and ammonia. By 1862 Liebig questioned this chemical reductionism, admitting that the real world of plant nutrition and agriculture was more complex and that chemistry could not provide comprehensive insight. His formulations became vaguer and left room for the unknown. Sometimes he came close to an ecological view of plants and their physical environment.

»In all his actions, the farmer must bear in mind that the plant is a living being«, Liebig declared in 1862, and »he must remove all harmful things and obstacles that interfere with the plant's activity«.[14] What kinds of harmful things and obstacles did he have in mind? Liebig did not offer a definite answer to this question, but he acknowledged that there were things and processes in the environment of plants that had not been unraveled by chemistry or any other science. The interaction between atmosphere, soil, nutrients, and plants depended on numerous unknown factors. Among other things, nutrients in the soil had to be transformed into appropriate states before they could be absorbed by plant roots. Nutrients needed to be made »diffusible« (*verbreitbar*) and »absorbable« (*aufnahmefähig*) for the roots, he wrote.[15] Liebig attributed an important role to the atmosphere in this process, but his explanations of how the atmosphere interacted with the soil and nutrients were elusive. All he said was that the atmosphere and the parts of the soil containing the nutrients »must come into contact with each other« and that a certain »duration of action of the atmosphere« was necessary »to bring a given quantity of nutrients in the soil into a state of diffusion and to make them available for absorption«. In this process, he added, mechanical tillage of the soil was important because it helped to move air into

14 J. Liebig: Die Chemie in ihrer Anwendung (1862), p. 139.

15 Ibid., p. 142.

the soil. Liebig also thought it possible that there were additional »external agents« that put plant nutrients into a »state of action«.[16] Obviously, this was no longer the language of a chemical reductionist. If we replace »external agents« with »environmental agents«, the emerging ecological view comes to the fore. Plants do not live and grow in a chemical container, but in a complex chemical-physical environment whose components and interactions scientists did not yet fully understand. Soil and atmosphere were the most important environmental components, but Liebig also allowed for additional »external« or environmental agents. Echoing the views of nature of his fatherly friend and supporter Alexander von Humboldt, Liebig wrote:

> »Our present study of nature is based on the conviction that there is a lawful connection not only between two or three phenomena, but between all phenomena in the mineral, plant, and animal kingdoms, which, for example, determine life on the surface of the earth, so that no phenomenon exists by itself, but is always connected with one or more other phenomena, and these with others, and so on, all connected with each other without beginning or end […]. We see nature as a whole and all phenomena as interconnected like the knots in a web.«[17]

This was a surprising move away from chemical reductionism and toward a new understanding of plants and their environment. What made Liebig change his mind? One incentive to reconsider the factors that influence crop growth may have been the failure of his chemical fertilizer. In the 1840s, Liebig had developed a set of chemical fertilizers for the major crops grown in central Europe. But he had not tested them in the field. The Liverpool-Irish manufacturer James Muspratt, a friend of Liebig's, and his sons took out a British patent protection on Liebig's behalf and began producing his fertilizers in 1845. Six types of fertilizer were produced for different types of crops, but when British farmers applied them, they found that the materials remained on the surface of the fields unless they were plowed in. The Muspratts tried to revise the manufacturing process to make the fertilizers more soluble in cold rainwater, but they still did not work well. Liebig explained this failure by the imperfect knowledge of how to make fertilizers suitable for their uptake and nutritive effect on the plant.[18] Nevertheless, several agricultural scientists and chemists harshly criticized him, most notably his German colleague Carl Fraas, as well as John Bennett Lawes and Joseph Henry Gilbert, who were conducting agricultural experiments with their own artificial fertilizers at the Rothamsted Experimental Station in Hertfordshire, England.

16 Ibid., p. 143.

17 Ibid., p. 87.

18 See Liebig, Justus: Chemische Briefe, Heidelberg: Akademische Verlagshandlung von C. F. Winter ^{3}1851. See also W. H. Brock: Justus von Liebig, p. 120–124.

John Bennett Lawes (1814–1900) was an English agricultural scientist, fellow of the Royal Society, landowner, and entrepreneur who patented an inorganic fertilizer and opened a factory to manufacture it in 1843. Shortly thereafter, he hired Joseph Henry Gilbert (1817–1901), a chemist and former student of Liebig's, to work with him on improving agricultural methods. In their co-authored book *Agricultural Chemistry*, published in 1851, they first praised Liebig's *Agricultural Chemistry* for stimulating an unprecedented »spirit of investigation« into agricultural problems, but then criticized it on the basis of their own field experiments. With an ironic tone, they wrote that they were interested in knowing »how far the facts of the last years had tended to alter or modify his [Liebig's] views on points wherein our own differed from those which he had hitherto published«.[19] One of these facts was that the »productive quality of a soil« could not be derived solely from knowledge of its chemical composition.[20] The physical properties of soils, their effect on the action of the dissolved plant nutrients, and the relationship between the soil and the atmosphere, they pointed out, must also be taken into account. All in all, Lawes and Gilbert argued that it was necessary to pay close attention to the »actual circumstances of the growth of each particular crop when grown under cultivation«.[21] Until 1851, Liebig had ignored all calls for a more complete examination of the environmental »circumstances« of crop growth. Neither the sixth edition of his *Agricultural Chemistry*, published in 1846, nor the new edition of his *Chemical Letters*, which appeared in 1851, made any concession to his critics. However, adding to the failure of his own artificial fertilizers, Lawes and Gilbert's *Agricultural Chemistry* must have given him food for thought.

The last edition of Liebig's *Agricultural Chemistry* had yet another surprise in store. Liebig regarded agriculture as the foundation of human well-being and the wealth of nations. By 1862, he had become familiar with economic theories, especially those of Adam Smith, and the problem of population growth. With a growing population, food supply was seen as a serious problem in many European countries. Agricultural production had »not kept pace with the increase in population«, Liebig noted, and »demand was greater and supplies were smaller than before«.[22] Hence, the question was not just how to maintain soil fertility, but how to increase soil yields. Could chemical fertilizers increase soil yields indefinitely, or were there limits? Again, Liebig was reluctant to give a definitive answer to this question. On the one hand, he had no doubt that complete recycling of plant nutrients would solve many of the existing problems of fertilization, but, on the other hand, he had

19 Lawes, John B./Gilbert, Joseph Henry: Agricultural Chemistry, Especially in Relation to the Mineral Theory of Baron Liebig, London: Clowes and Sons 1851, p. 1–2.

20 Ibid., p. 3.

21 Ibid., p. 7.

22 Ibid., p. 154.

become aware of the fact that the success of fertilization depended on additional factors. He pointed out that Great Britain had recently imported tons of bones and guano to add phosphate to the soil, but it was still unable to feed its population. One reason was that recycling was not complete. But there was another reason: »The immense quantity of manure which England imports every year«, Liebig observed, »flows for the most part down the rivers to the sea, and the products thus obtained are not sufficient to feed her increasing population«.[23] The example showed that there were limits to the capacity of the soil to absorb large amounts of fertilizer.

The problem of soil fertility was also challenging because of the unknown »external agents« involved in the process of plant nutrition. Liebig thought it possible that these external agents might be »limited in quantity« and »could not be increased by human labor«.[24] This was a noxious problem. If the external factors were rare or »limited in quantity« and »could not be increased by human labor«, they were an insurmountable threshold for intensifying agricultural production. At a certain point, the increase in crop yield would necessarily come to an end. The explosive social and political implications of this possibility are obvious. Philosopher Kohei Saito has pointed out that Karl Marx read all the editions of *Agricultural Chemistry*. Marx worried that science was about to show that there were ecological limits to agricultural intensification and hence to human welfare. However, there were other agricultural scientists, such as Carl Fraas, also read by Marx, who were more optimistic than Liebig.[25]

Carl Fraas: Botanist and Agricultural Scientist

Carl Fraas (1810–1875) was a professor of agricultural science at the University of Munich and an outspoken critic of Liebig's agricultural chemistry. There was too much chemistry in it. He also disagreed with Liebig's pessimistic view of agricultural overuse and its social consequences. While he recognized the twin problems of population growth and the overexploitation of farmland, he was convinced that humans could take precautions to maintain the fertility of farmland. Fraas's approach to agriculture was informed by his knowledge of botany, his experience of growing plants in botanical gardens, his agricultural field experiments, and his plant-geographical knowledge. A native of Bavaria, Fraas had studied botany and medicine at the University of Munich in the early 1830s. In 1837, he was appointed professor of botany at the newly founded University of Athens, as well as director of the Royal

23 Ibid., p. 129.

24 Ibid., p. 129.

25 See Saito, Kohei: Karl Marx's Ecosocialism. Capitalism, Nature, and the Unfinished Critique of Political Economy, New Dehli: Dev Publishers 2018.

Court Gardens and director of the newly established Athens Botanical Garden. After the Greek War of Independence against the Ottoman Empire, the Bavarian Prince Otto Friedrich von Wittelsbach had become King of Greece in 1832, which attracted many Bavarians to Greece, including Fraas. During his five-year stay in Greece, Fraas became a botanical expert and familiarized himself with the history of plants by reading classical texts. Upon his return to Bavaria in 1842, he first had a modest position as a teacher of natural history at the Royal Agricultural and Trade School in Freising. Three years later, he was appointed professor of chemistry and technology at the Royal Agricultural School in Schleißheim. In 1847, while still a professor at the Royal Agricultural School, he published a treatise entitled *Climate and Flora*, which paved the way for his appointment as extraordinary professor of agricultural science at the University of Munich in the same year. He became a full professor in 1851, just a year before Liebig began teaching at the Munich University. In Munich, he refined his agricultural studies and intervened in the discourse on agricultural overexploitation fueled by his Munich colleague Liebig.[26]

Fraas highlighted botany as the most useful science for agriculture, but he also drew on his knowledge of geography and plant history. As he explained in the introduction of his *Climate and Flora*, he intended to »describe the temporal changes in climate and plant life in the oldest inhabited countries on earth«.[27] He also wanted to make his findings useful for agricultural innovation. It was time, he wrote, »to devote more attention to the application of botanical knowledge to agriculture, trade and industry, art and commerce«.[28] In line with contemporary plant geography and agricultural science, Fraas focused on the relationship between plant communities, climate and soil. »Soil and climate are the essential conditions for the existence of plants«, he observed.[29] And as the »climate changes naturally, slowly, and continuously«, so do the plant communities. History had shown that changes in climate could cause desertification where once there were forests, grasslands, and fertile soil for agriculture and human civilization. This was a very important fact concerning »the habitability of the earth for humankind and its civilization«.[30] For example, the climate and flora of ancient Greece were very different from those of today. 2000 years ago, Greece had extensive deciduous forests, meadows, and fertile grain fields, but this landscape had almost completely disappeared, in part due to humans.[31]

26 For Fraas's biography see Zehetmair, Fritz Andreas: Carl Nikolaus Fraas (1810–1875). Ein Bayrischer Agrarwissenschaftler und Reformer der intensiven Landwirtschaft, München: Kommissionsverlag UNI-Druck 1995.

27 Fraas, Carl: Klima und Pflanzenwelt in der Zeit, ein Beitrag zur Geschichte beider, Landshut: Wölfle 1847, p. X. All translations are mine.

28 Ibid., p. VII.

29 Ibid., p. 6.

30 Ibid., p. 5.

31 See ibid., p. 4, p. 91–105.

Fraas argued that the climate was changing not only naturally, but also because of human activity. Large-scale deforestation for agriculture, he pointed out, affected the regional climate by increasing atmospheric temperature and decreasing precipitation, causing changes in the character of the vegetation. »The influences of humans and their civilizations on climate [...] are highly significant and essential to human existence«, he wrote.[32]

But it was not only climate change, natural and man-made, that affected a country's vegetation. Agricultural overexploitation was another important factor that often left behind barren land on which only frugal plants grew. The latter was clearly a point on which Fraas agreed with Liebig. The introduction of foreign crops was another human activity that could disturb native plant communities. Fraas viewed the natural vegetation of a place as a unified whole, the character of which could be irreversibly altered by natural or man-made changes such as the introduction of alien crops. »A profound violation of the natural vegetation of a country«, he warned, »leads to a profound change in the entire character of the vegetation [...], which can seldom be undone later, and if on a large scale and connected with many countries, cannot be undone at all«.[33] This, he added, should be taken to heart by governments that attempt to rebuild once-flourishing agricultural lands and civilizations.

Fraas also highlighted the role of soils for plant growth. Although he agreed with Liebig's mineral theory of plant nutrients, he criticized his chemical approach as one-sided. As has been shown above, in 1840 Liebig regarded the soil and the atmosphere as passive chemical containers of plant nutrients. By 1862, he revised this view, but his new ecological views remained vague. Fraas, on the other hand, articulated his ecological ideas quite clearly. He argued that the soil interacted with climatic factors, especially air temperature and precipitation, and that this interaction affected the decomposition of organic plant remains into inorganic materials as well as the weathering of rocks, which provided additional mineral nutrients. »Does not the weathering of rocks, which is so dependent on atmospheric precipitation and temperature, and therefore on climate, proceed quite differently in different climatic zones?« he asked rhetorically.[34] Fraas went so far as to argue that »fertilizers are often made unnecessary by the climate«.[35] Ten years later, he detailed the interactions between, soil, climate and plant nutrients as follows:

> »1. The more the soil is exposed to the alternation of heat and cold, wetness and dryness, the faster the weathering progresses. 2. Weathering is accompanied by

32 Ibid., p. 3.

33 Ibid., p. XII.

34 Ibid., p. 53.

35 Ibid., p. 54.

an increase in the solubility of plant nutrients. 3. Under constant extreme cold, weathering proceeds slowly, while under constant extreme heat, weathering proceeds more rapidly. Constant wetness and dryness have the same effect. 4. Mechanical reduction in the size of soil particles […] promotes weathering.«[36]

According to Fraas, soil played an active role in the distribution of plant nutrients and their delivery to plant roots. »Soil plays a very important and underappreciated role in the distribution and delivery of nutrients that come from it or are added to it«, he wrote.[37] In addition to the minerals contained in the soil, carbon dioxide and nutrients dissolved in rainwater entered the soil from the outside and were subsequently ›absorbed‹ by the soil particles. And the tangling of plant roots around the soil particles allowed them to take up the nutrients. All in all, Fraas developed a sophisticated ecological model of the interactions between rock weathering, plant nutrients in both their gaseous and dissolved forms, soil particles, and plant roots, which included the reciprocal effect of feedback from plant roots on weathering and thus on nutrient supply. The notion of feedback cycles had not yet been introduced at the time, but this is what Fraas described:

»Because of the adhesion of gases and substances dissolved in water to the solid parts of the soil, the finest ends of the *roots of plants* always cling to the parts of the soil, even to apparently completely insoluble grains of sand and much coarser parts, *whose weathering they also promote*. And the soil, depending on the degree of weathering and the consequent dissolution of minerals, and depending on its capacity to absorb gases, slowly and very moderately releases its nutrients, but inexhaustibly and without disturbing the harmonious existence of the plants.«[38]

The second part of Fraas's statement also postulated that the process of nutrient supply by the soil was adapted to the needs of plant life, and that plants and soil thus formed a harmonious whole.

Like Liebig, Fraas drew environmental policy conclusions from his ecological insights. These were fueled not least by Liebig's last edition of *Agricultural Chemistry*, published in 1862, which warned of a serious crisis for humanity if agriculture did not fully embrace chemical fertilization. In 1866, Fraas published a treatise entitled *Crises of Agriculture*, which presented his own views on the subject along with a polemic against Liebig. Given the fact that the two men lived in Munich and taught at the same university, the book must have been a sensation. At the heart of the polemic

36 Fraas, Carl: Die Natur der Landwirtschaft. Beitrag zur Theorie derselben, München: Literarisch-artistische Anstalt der Cottaschen Buchhandlung 1857, p. 11; all translations are mine.

37 Ibid., p. 74.

38 Ibid, p. 75 [my emphasis].

was the maintenance of soil fertility. Fraas shared Liebig's view that the plant nutrients absorbed by crops had to be completely replaced by manure and that soil depletion was a major problem of the day. »If man does not properly replace what he has taken from the soil, he will have exhausted the land in a few years«, he pointed out.[39] In contrast to Liebig, however, he did not recommend chemical fertilizers. He admitted that »in many cases artificial fertilizers are an excellent means of increasing the yield of our fields«, but he warned that »they are not the great remedy for agriculture in the present and future. They are not the great panacea against the extinction of nations through soil exhaustion«. Why was this so? Fraas did not present chemical or physical arguments against chemical fertilizers but brought economic arguments into play. »Due to the rarity and high price of their active ingredients«, he argued, chemical fertilizers »cannot have the great economic importance that the supporters of the mineral theory would like to attribute to them«.[40] The alternative, in his view, was irrigation and the utilization of alluvial soil. In ancient times, Fraas wrote, the most important precautionary measure against land plundering was fertilization with alluvium, and he argued emphatically for this alternative method:

> »The most important consequence of the new theory of plant nutrition is not the old, now generally accepted conviction of the necessity of replacing the soil components removed from the cultivated areas by the harvest, but the discovery of numerous sources for increasing them. In addition to the so-called artificial fertilizers, irrigation with alluvium is of the highest priority. This means free fertilization via the water supply.«

As rivers contained minerals stemming from rock weathering, they were man's unbeatable means »to exploit the mineral resources of the mountains«.[41]

Fraas argued on the basis of his alluvial theory that »the doctrine of the increasing exhaustion of the arable land of all peoples and their consequent decline«, was a »false assumption«.[42] In early civilizations land overuse was less pervasive than was often assumed, because precautions such as artificial alluvial fertilization were taken. Fraas was convinced that population growth in Europe was not reaching the limits of food supply for a very long time. »The population of Central Europe«, he declared in stark contrast to Liebig, »can still grow immensely until it has to experience a lack of food«.[43] He concluded with the following optimistic scenario: »The effective ingredients of all fertilizers, the most expensive plant nutrients, are most cheaply

39 Fraas, Carl: Die Ackerbaukrisen und ihre Heilmittel. Ein Beitrag zur Wirthschaftspolitik des Ackerbauschutzes, Leipzig: Brockhaus 1866, p. 213; all translations are mine.

40 Ibid., p. 155.

41 Ibid., p. 156, p. 158.

42 Ibid., p. 212.

43 Ibid., p. 156.

available in water and are, for the time being, inexhaustible. This is why rivers have been and still are the inexhaustible source of field fertility for peoples in ancient and in modern times.«[44]

If we compare the environmental views of Fraas and Liebig, we see that they evolved in opposite directions. In the 1840s, Liebig's environmental policy message was still moderate, while Fraas presented a fierce critique of man-made environmental degradation. At the time, Fraas was convinced that the entire history of human civilization had been accompanied by irreversible damage to the Earth. »The advancing civilization has left a desert in its wake«, he wrote in 1847.[45] He also believed that it was a waste of effort to try to make formerly fertile but now barren land, such as much of Greece, arable again. By 1862, however, Fraas had become a political optimist. Liebig, on the other hand, had become a political radical who warned with apocalyptic scenarios that overexploitation of the land would ultimately lead to terrible wars.

Conclusion

In the first half of the nineteenth century, soil depletion caused by intensive agriculture was a hotly debated topic among European scientists, agronomists, economists, and state officials. Justus Liebig, Carl Fraas, John B. Lawes, and Joseph Henry Gilbert belonged to a group of scientists and agronomists who discussed the possibility of maintaining soil fertility by means of artificial fertilizers. Liebig argued for the complete recycling of plant nutrients and warned governments that overexploitation of arable land could jeopardize the food supply for future generations and lead to terrible wars. After the practical failure of his chemical fertilizer, he abandoned his rigid chemical approach to plant growth, admitting that he had underestimated the complexity of ecological relationships. He also admitted that there might be limits to artificial fertilization and further intensification of agricultural production. Fraas, on the contrary, believed that proper methods of fertilization would ensure humanity's food supply for many generations to come, even as the world's population grew. He developed a complex ecological model interconnecting climate, rock weathering, soil processes, plant nutrients, plant growth, and the character of vegetation in different climatic regions, including the feedback of plant root activity on rock weathering and thus on nutrient supply.

Liebig's and Fraas's agricultural sciences addressed agricultural techniques, plant nutrition and growth, the ecological relationship between plants and their environment, and the social and political significance of agriculture. Their mixing

44 Ibid., p. 164.

45 C. Fraas: Klima und Pflanzenwelt, p. 59.

of technological issues, natural science, and socio-political reasoning was by no means exceptional. Rather, it was typical of the so-called practical or useful sciences of the late eighteenth- and nineteenth centuries. For example, the mining science of the time was a loose assemblage of mining technology, administrative knowledge, geology, mineralogy, and analytical chemistry. To take another example, nineteenth-century technological chemistry combined technical knowledge of a particular industry, such as dyeing or porcelain making, with useful chemical knowledge. Like agricultural science, mining science and technological chemistry juxtaposed knowledge from different fields and constructed their research topics and methods without the goal of creating a fully integrated, logically coherent system of knowledge. The practitioners of these sciences also participated in discourses broadly concerned with human wellbeing. The practical scientists' orientation toward applicability correlated with their overall epistemic goal of developing ›reliable knowledge‹, useful with respect to particular sets of the material and social world, rather than universal truths. Yet, despite the differences in the overall goals of the nineteenth century practical sciences and natural sciences the research practices of these sciences shared many features.[46]

46 See U. Klein: Technoscience in History.