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WILLIAM RUDDIMAN AND THE RUDDIMAN HYPOTHESIS

By Richard J. Blaustein

Trained as a marine geologist, University of Virginia emeritus professor William Ruddiman for the past fifteen years has worked on a hypothesis that posits that pre-industrial age humans raised greenhouse gas levels in the atmosphere. Looking back seven thousand years into the Holocene—the current 11,500-year-old geological epoch—Ruddiman has proposed that early agriculture emitted enough methane and carbon dioxide to offset what would have been a global cold cycle. Ruddiman says that in contrast to the familiar view that human-caused greenhouse gases began with the industrial revolution, "the baseline of human effects on climate started earlier and that the total effect is larger." Ruddiman's work and "the Ruddiman hypothesis" provide a classic illustration of the working out of a scientific theory, with detractors, new allies, and new technologies and facts that bear on the original idea.

University of Wisconsin climate scientist Steve Vavrus has worked on the modeling for Ruddiman's investigation, and he sees a two-fold implication for the Ruddiman hypothesis. "This hypothesis is arguing that the significant footprint of human add-on to climate began thousands of years ago and not just 150 years or so, which is the conventional view. So it really changes how we perceive the timing of human impact on the global climate system." Vavrus continues, "and then the future part I think is important too because if this hypothesis is right and [if] humans—who were very few in number compared to the present day… did have a significant impact on global climate, then I think it is all the more reason to be concerned that many more humans who exist today with much greater technological footprint will probably have a bigger impact on global climate."

Even today climate scientists are not in total agreement as to whether early agriculture had a significant impact on global climate. Penn State climate scientist Richard Alley, for example, responds in an e-mail, "I believe that many, and probably most, members of our field think that the early human greenhouse gases had a small effect on climate, but not a large one…Not everyone agrees, however."

Nonetheless, in recent years support for Ruddiman's hypothesis has broadened. Archaeologists and ecologists have contributed by collecting data on early agriculture—for example, rice paddy cultivation that is linked to methane emissions. Additionally, former estimates concerning the amount of land deforested and cleared for agriculture have been revised upward.

In an important development, a 2013 study, "Constraints on the Late Holocene Anthropogenic Contribution to the Atmospheric Methane Budget," analyzed another pairing of ice cores and corroborated the proposition that humans significantly caused methane release for the study's focus of twenty-eight hundred to five hundred years before the present. University of Utah geologist Logan Mitchell, the lead author of this article, which was published in the journal *Science*, explains in an e-mail that his and his co-authors' study uniquely "links the concentrations of methane from the northern and southern poles found in ice cores to spatial distributions characteristic of natural and human activity."

According to University of Maryland landscape ecologist Erle Ellis, who has co-authored recent papers with Ruddiman, the *Science* paper is something of a turning point. After the *Science* paper, Ellis says, "It is going to be very hard for anyone to disprove that there is a very large human methane signal in the middle of the Holocene." Ellis does feel, however, that linking pre-industrial rising carbon dioxide levels with human

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land use will be harder to prove. Complex factors—such as peatlands' serving as both carbon sources and sinks, for example, and oceans' dynamics—play a significant role in the carbon cycles, and are difficult to assess thousands of years ago. Ellis says that for the pre-industrial carbon levels, "in terms of an empirical smoking gun, I have to say it is not there yet." Certainly, many questions remain. Meanwhile, Ruddiman and colleagues are enhancing their cross-disciplinary collaboration to better understand the greenhouse gas impact of early agriculture.

EARLY THINKING, EARLY RESPONSE

Ruddiman began his thinking about early agriculture and greenhouse gases in the late 1990s when new Greenland and Antarctic ice core data was made public. Examining the data, Ruddiman was puzzled by the rise of atmospheric methane around five thousand years ago.

In the glacial cycles of the past four hundred thousand years, this natural methane emissions rate is linked with the earth's approximate twenty-two thousand precession cycle, the orbital cycle in which the earth shifts its axis of orbit, wobbling a bit like a spinning top. When the northern hemisphere summer is closest to the sun via precession, the highest amount of global methane is emitted. In the current interglacial precessional cycle, the methane maximum occurred eleven thousand years ago, at which there was the expected seven hundred parts per billion (ppb) methane concentration in the atmosphere—expected because comparable interglacial periods have that methane level.

However, at around five thousand years ago, Ruddiman noted that instead of continuing downward to a 450 ppb level, the methane leveled off at 560 ppb, and, reversing course, rose to around 660 ppb by one thousand years ago. Ruddiman correlated the methane trajectory reversal with rice paddy agriculture in Asia, which intensified roughly around the same time, five thousand years ago.

Methane is a natural product of decomposing submerged organic matter with, for example, marshes and other wetlands emitting swamp gas. Although there was, and is, unirrigated rice agriculture, rice paddy agriculture—which enhanced the domestication, harvesting, and nutritional value of rice—involves raising rice in stagnant water. After harvesting, the rice paddy areas emit methane in a similar manner to that of natural wetlands' organic decomposition.

According to a recent study led by archaeologist Dorian Fuller, "The Contribution of Rice Agriculture and Livestock Pastoralism to Prehistoric Methane Levels: An Archaeological Assessment," the irrigated rice agriculture began in the Lower Yangtze area of China around six thousand years ago and not too long after spread to other parts of China. By four thousand years ago, many other parts of Asia had rice paddy agriculture, correlating with Ruddiman's linking of rice agriculture with the anomalous methane rise.

Ruddiman also noticed a similar trajectory for carbon dioxide. Unlike the methane cycle, the more complicated carbon cycle is set not just by the precessional cycle but is also linked to the other long-term earth orbital determinants, eccentricity (orbit around the sun) and obliquity (the earth's tilt). Nonetheless, there is a clear pattern for carbon dioxide declining from approximately 285 parts per million (ppm) around 10,500 years ago. This is what was expected based on prior periods of interglaciation. However, the carbon trajectory reversed around seven thousand years ago, a time when agriculture expanded. By the time of the industrial age, it was 40 ppm higher than the expected 245 ppm.

While he began publishing on the topic in 1999, Ruddiman first fully articulated his hypothesis in 2003 in "The Atmosphere Greenhouse Era Began Thousands of Years Ago," an article in the journal *Climate Change*. That same year he spoke to a large audience at a December gathering of the American

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Geophysical Union, which he credits with advancing the discourse on his idea. In 2005 he widened his audience by writing a *Scientific American* article, "How Did Humans First Alter Global Climate," on the same subject. Ruddiman has published on his hypothesis as recently as 2014.

By the mid-2000s, Ruddiman's hypothesis intrigued many people. His analysis was bold: for example, in the 2005 *Scientific American* article, he wrote, "as I see it, nature would have cooled earth's climate, but our ancestors kept it warm by discovering agriculture."

According to Ruddiman, it was not easy going at first. In the early days, even some of Ruddiman's climate scientist colleagues strongly disagreed with him. "For a while I felt like I was mostly arguing with climate scientists and especially geochemists who just didn't think people could possibly be affecting atmospheric greenhouse concentrations that far back because there weren't enough people who could alter the landscape enough," he says.

In another twist, which Ruddiman remembers as a bit strange, vocal climate change skeptics who were bloggers tried to use his views to bolster their arguments against responding to climate change. "The gist of their argument," recounts Ruddiman "was greenhouse gases must be our friend because they stopped the glaciation. So that is the way they were arguing it and that is a twisting of what I said."

The illogic of the blogger-skeptics views soon became apparent. On one hand, they denied that humans were causing greenhouse gas–induced warming; and on the other, they were delighting in a new theory, based on mainstream science, that stipulated anthropogenic causes for climate change. According to Ruddiman, the bloggers "quickly realized they had let the Trojan horse inside the walls, and they all of sudden dropped any mention of my research because they realized they were opening themselves up to criticism."

Ruddiman admits, however, that there were uncertainties and open questions in his original hypothesis that needed addressing. "I basically spent most of the past ten years trying to track down weaknesses in my hypothesis," he says. "I think I met those challenges pretty much across the board—that's where I tend to spend my time mentally thinking about it."

THE RUDDIMAN HYPOTHESIS AT PRESENT

In recent years, new collaborations and independent investigations have bolstered Ruddiman's efforts. Moreover, Ruddiman's figures, such as for atmospheric methane and carbon dioxide levels, have remained about the same, although he has modified the turning point for agriculture's link to carbon dioxide emissions at seven thousand instead of eight thousand years.

In 2014, Ruddiman and colleagues published findings estimating that the human-caused, pre-industrial warming had an approximate 1.2 Kelvin effect. The post-1850 rise in temperature is .85 K, and the Ruddiman group, which includes Vavrus, concludes that the combined effect of the pre-industrial warming and industrial warming is twice that of the industrial age warming alone. Importantly, they underscore that this occurred over thousands of years, unlike the less than two century scale of the current greenhouse gas effect.

Vavrus and Ruddiman both point out that the net temperature effect is still a slight cooling for the earlier period. They calculate the 1.2 K effect from models with and without human effects. They both point out that what the anthropogenic warming did was to significantly, but not totally, cancel the natural cooling dynamic caused by the precession cycle. "Were it not for that artificial warming, the climate system probably would have cooled significantly," Vavrus says. "The net effect of early anthropogenic warming is larger, we think, than it would appear simply by taking

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a temperature difference, between 1,850 and 6,000." Vavrus explains that a rough estimate of both warming and avoided cooling would be about 0.6° C for both.

Vavrus and Ruddiman are quick to clarify that without pre-industrial greenhouse gases there is the possibility the earth would have experienced a "glacial inception," which is less comprehensive than a glacial age. Their modeling, however, has come up with year-round snow cover in areas that have only seasonal snow. While this snow might have compressed to form ice sheets, Vavrus emphasizes that it is very difficult for a model to recreate glacial formation because it takes up so much computational time.

Ruddiman, however, does flesh out what this glacial inception could look like. He writes that there would be yearly snow cover in "several regions, including the northern Canadian Rockies, the Canadian archipelago, the northern Arctic margin of Eurasia and eastern Siberia." While pointing out that this year-round snow would cover an area larger than Greenland, Ruddiman states that any ice forming from the snow would have nowhere near the thickness of a Greenland ice sheet.

Underpinning these recent estimates, refined land use assumptions have been an important recent addition for the Ruddiman hypothesis. The new thinking began during the late 2000s while many were challenging Ruddiman's ideas, claiming the smaller population thousands of years ago did not convert much land to agriculture.

Ellis recounts meeting Ruddiman at a 2008 American Geophysical Union meeting and discussing with him the extent of land use during the early agriculture period. "The question he asked me [was] is it possible that people in the past used more land per person than they used today?" says Ellis. "And from my point of view, from my experience—and really pretty mainstream experience—is that obviously they used a lot more land per person in the past. Land was basically free back in the origins of agriculture. There was no land shortage. People used the least labor methods which is burning out the landscape and throwing out a few seeds…They used large amounts of lands per person to farm."

Around the same time, ecologist Jed Kaplan was modeling historical land uses and vegetation patterns, and Kaplan also met Ruddiman at an American Geophysical Union meeting, this time in 2009. Kaplan became interested in applying his land-use models to early agriculture greenhouse gas emissions questions. In Kaplan's modeling, he combines complex land-use surveys, computer modeling, archaeological data, and extant historical land records from as far back as he can find them to estimate historical land-use patterns. His findings have revised earlier baseline estimates for land use, which basically extrapolate recent per capita land use retroactively.

In a 2011 Kaplan-led study, "Holocene Carbon Emissions as a Result of Anthropogenic Land Cover Change," which included Ruddiman and Ellis among the coauthors, Kaplan and his team concluded: "Archaeologists, paleoecologists, paleobotanists, anthropologists and other field-based researchers have repeatedly shown that from the late Paleolithic to the beginning of widespread industrialization, the first human residents and especially farmers in any region used far more land per person than those after them, and that land use per capita has decreased over time as population increase."

The Kaplan land-use model greatly bolstered the Ruddiman hypothesis. It doubled the carbon dioxide emissions in the past seven thousand years relative to a linear model, with the Kaplan model now estimating 343 billion tons of carbon emitted during pre-industrial times. This would have accounted for 24 of the 40 ppm rise in carbon dioxide relative to a pre-industrial world without anthropogenic greenhouse gases.

Like Ellis, Kaplan agrees that the actual definitive proof of anthropogenic carbon dioxide will come from some form of hard (e.g., isotopic or ice core) evidence.

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Kaplan also raises the point that Vavrus and Ruddiman make that ocean processes probably account for a significant amount of the 40 ppm carbon dioxide pre-industrial rise. Ruddiman says that this ocean activity could have been instigated by the anthropogenic greenhouse gas releases.

Yet Kaplan also says that it is illogical to assume that pre-industrial human activities had no effect on atmospheric greenhouse gas levels. “I do not believe you can explain the Holocene record of atmospheric carbon dioxide concentration without invoking some kind of anthropogenic source, and I think this is kind of the key message here,” Kaplan says. “We have to realize that the Holocene is a very special time in Earth history. It is the only time in Earth’s history when humans lived everywhere on the planet and where we undertook activities like deforestation, like agriculture, like domestication of ruminant animals and urbanization and metallurgy and all of these other kinds of uniquely anthropogenic habits that lead to greenhouse gas emissions.”

Archaeology is another field in which Ruddiman’s argument is finding some support. Prominent among his supporters is University College London archaeologist Dorian Fuller, who has investigated early rice agriculture and its connection to methane levels. Fuller and colleagues reviewed “archaeobotanical evidence for 385 sites including 443 individual site/phase data entries, with a focus on rice in Asia” for the period of five thousand to one thousand years ago. They concluded that rice paddy agriculture in Asia would have logically emitted enough methane to account for 70 percent of 100 ppb methane increase found in the ice record for this period. Fuller and colleagues also used the Kaplan-type of non-linear land-use assumptions. The archaeologists are also considering the impact of livestock on early methane releases but have not yet quantified the livestock-methane connection. The figures will certainly be significant because livestock are methane-emitters, and their diffusion was more widespread than rice.

Ruddiman is gratified that different fields and disciplines that are now interested in his hypothesis. Yet their contributions also underscore how difficult and large a question pre-industrial greenhouse gas emissions is. “The argument is not going on within a specialty, it is going on across specialties,” Ruddiman says. “And so it is really almost no one who knows all these specialties. There are so many specialties you have to be knowledgeable in. So it is a tough argument for people to get into. They’ll get into the part of the argument that has to do with their specialty. The overall argument is very broad and crosses specialties.”

TASKS, WORRIES, AND HOPES FOR THE FUTURE

The Ruddiman hypothesis is a work in progress, with new participants and disciplines offering inputs and assessments. Some have ideas on how corroborations can be enhanced and pressing questions addressed.

Vavrus has been thinking about this. He talks about the next stage of modeling, which moves beyond inputting atmospheric greenhouse gas levels and focuses on emissions running their course. “We have not run the models with an interactive carbon cycle,” says Vavrus. “It would be more realistic—and it is on our to-do list—to try to instead input emissions of carbon for early agriculture and then use those to drive the climate model, and then let the climate model simulate what would happen to the concentration of methane and carbon dioxide based on feedbacks that happen within the climate system.”

Another common reflection connected to the Ruddiman hypothesis is how much greater is the current climate change forcing. Ellis explains: “What you are talking about here is changes of parts per billion in methane, a change of 10 or 15 percent concentration that took place over thousands of years. . . . What we are talking about today is tens of years. The rate of the change is not even remotely comparable.”

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Vavrus emphasizes the same point. "To me it is a warning sign that if we could have done so much with so little in the past, what we are doing today has gargantuan implications for climate change."

Ruddiman shares the concern about overwhelming the earth system. But he also finds some hope for the future when he looks back at early agriculture. "One of the lessons that I've learned is that the story of agriculture, a considerable part of it, is the story of human resilience," Ruddiman says. Recalling the Malthusian prediction of overpopulation and famine, he reflects that "as populations grew and people got pushed back unto smaller amounts of land, they became more and more clever about how to get food off of these small plots. So it is a story of human innovation and technological advances of how to avoid the consequences of population disasters and food shortages. It is quite a remarkable story."

"So perhaps there is a small ultimate hope for the future that we will do that as we have to worry whether we are going to...massively alter climate," Ruddiman concludes. "Maybe we will be able to innovate our way out to avoid the worst consequences of our own actions...Because that is certainly the history of agriculture—technological innovation that allows people to get more food off of less land."

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FOR FURTHER READING

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