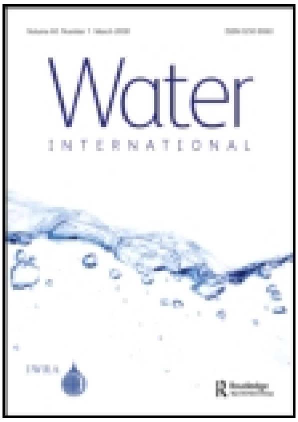

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Are we killing the rain? Meditations on the water cycle and, more particularly, on bioprecipitation

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Are we killing the rain? Meditations on the water cycle and, more particularly, on bioprecipitation

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This essay reviews the multidisciplinary science of bioprecipitation, using it as a lens through which to envision integrative options for land use and water resource management in a new light. Bioprecipitation is the hypothesis that microbial ice nucleators, including *Pseudomonas syringae*, may be highly adapted causal agents of rain and snow. To the extent that land use policies, including pathogenic eradication campaigns, may inhibit the local production of biotic ice nucleators, they may be responsible for 'killing' a generative source of rain. Such possibilities should invite major interest in this gathering field of research. Assuming that it contributes to a richer comprehension of the hydrological cycle's dependence on circulatory biota, these findings should help to stimulate assimilative, integrated reformulations of land use and water management policies and norms.

Keywords: rain; precipitation; bioprecipitation; integrated land and water management; over-grazing; public lands

A growing body of scientific literature that relates to an hypothesis – actually, a small cluster of hypotheses – known as 'bioprecipitation'[1] offers a path to a new appreciation of human agency as a distinctive cause of local and regional climate change, a shift of focus from change on a global level. It pertains to a subject that is nowhere yet on the public's agenda or that of policy makers, one that could promote an instrumental focus of global significance on the integration of land use and water resource management through a systematic effort to invite the production of rain and the disinvitation – that is, the inhibition – of drought.

The basal understanding at the root of this aptly named idea is that atmospherically transient biological materials, especially microorganisms, are efficient producers of ice crystals in an abundance that fosters their descent to the earth as rain, snow and ice. Within this formative view is a secondary hypothesis. It is that the most efficient contributors to ice nucleation (IN)[2], as this activity is called, may be certain varieties of bacteria that populate many, if not all, regions of the world. These have already been discovered as the nucleus of snow and rain on five continents, with tantalizing frequency in heavily cultivated agricultural regions. Their ancient role in this capacity may soon be demonstrated through the coring of glacial ice (Christner 2012).[3] A third hypothesis that nests inside these two is that a particular bacterium, *Pseudomonas syringae*, is the most proliferative

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ice nucleator within a range of relatively warm atmospheric temperatures in which other nucleators may lose their effect. Currently, *P. syringae* is ubiquitously known and treated as a plant pathogen, damaging its favoured hosts, certain agricultural crops, by employing its talents for propagating ice.

The practical excitement that lies within the compass of these discoveries resides in the possibility that the most effective bacterial ice-nucleation agents could be cultivated, just as food crops are cultivated, for their value in inducing rain. The dark seed of discovery that may lie further within this domain is that common land use policies may be having just the opposite effect. It is this possibility – that land use policies are inhibiting the proliferation of important ice-nucleating microbiota – that is the inspiration for this essay's title and for its intended work.[4]

In both title and form, the 'Meditations' that constitute a portion of this essay are tempered by the state of the relevant science, which is, in important respects, immature. As one microbiologist has put it, "Recent developments challenge the belief that microorganisms are passive travelers in the atmosphere. Indeed, evidence that microorganisms affect meteorological processes is invigorating research to define the role of biology in atmospheric processes and to understand how those processes might affect the abundance, dispersion, and viability of aerosolized microbes" (Christner 2012) – among these, the kinds of microbes, as he goes on to explain, that have been found to nucleate rain.

The careful use of the term 'might' in this statement sketches the present divide between the known and the unknown. (See further Morris and Sands 2012.) Such a rendering should make it clear just where in the timeline of research any attempt, such as mine, to lasso public land use and water resource policies to the bioprecipitation hypothesis will enter the public arena: earlier than may be due. Still, it is difficult not to become engaged by the excitement to be found within the multidisciplinary science that is at work, as the literature review that follows intends to show.

Most recently, bioprecipitation scientists have also sought to gain popular notice for this research (Fox 2012, Morris and Sands 2012, Sands 2012), a signal that, in their view, its most basic findings are ready to enter the public conversation about climate variables. It may not be too early, after all, for ideas that demonstrate the muscular reformative capacities of the research, especially in relation to land use, to begin to emerge. In fact, they already have (see e.g. Sands 2012).

My goals in writing this essay, then, are two. One is to spread word about bioprecipitation theory into the policy realm because of the paradigm-shifting potential that it reveals. The second is to winkle out some early thoughts about the practical implications of this work.

Bioprecipitation: a literature review

Conventional explanations of precipitation rely principally on meteorology and cloud physics. They bear major evidence of their dependence on the physical sciences, from which they branch. A standard meteorological definition of "precipitation" is: "Any product of the condensation of atmospheric water vapour that falls under gravity" (American Meteorological Society 2009). The referents within this concise portrayal expand into a congeries of inquiries concentrated, within the atmospheric sciences, on the processes that initiate and direct water vapour saturation and condensation and on the relationship of these processes to such vital influences as temperature, humidity, pollution, and the extent and direction of motion within the cloud-types prevalent at different levels within the atmosphere (see, e.g., Keil *et al*. 2008). Study of these extremely dynamic processes presents significant challenges, not least because cloud systems are too vast to subject to controlled study, as opposed to observation in situ, yet too complex and interdependent to render fully through mathematical models and other bounded means (Stratmann *et al*., in Heintzenberg and Charlson 2009, p. 150). Recent syntheses of the work being done in cloud physics includes critical analyses of the present state of knowledge in regard to major elements of cloud systems, with explicit attention drawn to knowledge deficits, methodological inconsistencies, and other bases for needed development within the field. Accelerating “perturbations” within the climate system provide a hard spur for improvements to be made (see generally Heintzenberg and Charlson 2009).

Beyond contest or revision lies the fact that water droplets can coalesce on account of collisions with other droplets or on account of the formation of ice crystals within clouds. The crystals can form around nuclei composed of either inorganic matter, such as dust, salt or minerals, or organic matter, such as algae or bacteria. Without the intervention of the biological sciences such as the microbiology, genetics and plant pathology that have spearheaded bioprecipitation research, the physical-science view of ice nucleation seems to stop at this door, behind which the crystallization process is taken to be adventitious, temperature dependence being the major determinant of nuclear type (Fox 2012, p. 42), while efficacy in the nucleation process remains unexplored.

In a curious way, what I might term the ‘nuclear indifference’ hypothesis has been subject to a kind of crude refutation, although it is not yet complete: Prolonged efforts involving both scientific and practical experiments and applications stretching across decades and continents have, with rare exceptions, failed to yield proof of scientifically-accepted status that the ‘seeding’ of clouds through the variously-engineered injection into them of specific types of inorganic particles can function to enhance the formation of rain (NRC 2003, Cotton 2009). To be sure, explanations of these failures run in several directions not centred on the organic versus inorganic nature of the seeding agent (Beck 2010; Cotton 2009; Levin 2010). For immediate purposes, it is enough to understand that the widely-noted scientific deficiencies of cloud-seeding experiments involving the introduction of inorganic particles into clouds should cast no aspersions on the development of the field of bioprecipitation which, in its aims, methods and outcomes, is entirely remote from the cloud-seeding oeuvre.

The focus of agronomy on agricultural yield was where the field got its start. Research led to the discovery of diseases that attack specific types of edible plants. Indeed, a single pathogen, the bacterium *Pseudomonas syringae (P. syringae)*, was found responsible, on a non-exclusive but highly persistent basis, for disease vectors that injure (though they typically do not destroy) an impressive variety of plants.[5] The function of much modern agronomic research has been to locate and develop effective agonists to respond to agricultural blights, including those caused by *P. syringae*. This research has led to the discovery and wide dissemination of several effective, though not wholly successful, bactericides (see e.g. Bashan and de-Bashan 2002a, 2002b).

An obvious research question involved the method by which *P. syringae* enters plants with the impressive success that it demonstrates. Two teams working independently in the 1970s discovered that *P. syringae* bases its propagative success on its ability to cause frost damage, primarily to leaves and stems, the torn and split tissue then providing a means for bacterial entry into the host plant, a metabolic activity that a specific range of temperatures was found to promote (see e.g. Arny *et al*. 1976, Vali *et al*. 1976). This, *P. syringae* is able to accomplish through its specialized ability to bind to water, the talent of a rare gene that codes for a crystal-inducing peptide lattice in the outer cell wall, found in just three of the microbe’s 600 known strains thus far (Morris *et al.* 2004).

Further investigation included the question of how *P. syringae*, which appears to migrate over vast distances, negotiates its passage through the air. Professor David Sands, who has studied this bacterium for over 40 years, hypothesized that the same property that lends efficacy to its ability to bind water to plant surfaces might also promote *P. syringae*'s ability to mobilize, after dissemination into the atmosphere due to radiative fluxes, and to nucleate ice there. Still, the question remained: How? The concise answer is that *P. syringae* utilizes the same method for catalyzing atmospheric ice crystals as it does for inducing ice nucleation on plants: its highly adapted ability to bind water to the surface of its cell (Christner 2012, Morris and Sands 2012).[6]

It took three decades for bioprecipitation research to reach the discovery just described. The basic hypothesis – that ice nucleation may be spurred by biological agents – was advanced by three different research teams some 30 years ago (Lindow *et al*. 1976, Sands *et al*. 1982; Vali *et al*. 1976). Earlier work had prepared the way (see e.g. Soulage 1957, Schnell and Vali 1972, Maki *et al.* 1974, Vali 1968, 1971). Substantial doubt followed the introduction of this idea. There was widespread scepticism that biotic masses large enough to be of influence could attain sufficient loft to enter, let alone subsist within clouds. Research support dried up. According to Sands, the field "collapsed" (Fox 2012, p. 42). The theory could not be well tested through field study. Its validation through wide replication has required DNA testing not then available. Further evidence, involving satellite-based meteorological technologies, again unavailable earlier, requires funding levels the scientific groups involved in this highly dispersed field have yet to acquire, though a recent, path-breaking study using atmospheric modelling has been performed (Goncalves *et al*. 2011). As the field has grown more ambitious (Christner 2012, Morris and Sands 2012), it has conjoined the biological- and physical-science components of the work. Currently, it involves cross-disciplinary collaborations of geneticists, geophysicists, meteorologists, microbiologists, plant pathologists and statisticians, among others. With the advent of these techniques and the assemblage of these teams has arrived the ability to test appropriately the various embedded claims.

As of this writing, positive findings related to biological ice nucleation have been confirmed by some 40 scientific teams working out of dozens of laboratories in at least six countries. The work has advanced substantially just since 2005. Among others, David Sands and Cindy Morris and their colleagues have published some definitive research (Christner *et al.* 2008a, 2008b). This work has confirmed the general bioprecipitation hypothesis through consistent findings.

Atmospheric scientists have recently added a new and powerful arm to these discoveries. In early research, they have demonstrated the potential of biological agents to act as cloud condensation nuclei (CCN) in addition to their IN activity. Through this added process, biological agents can "contribute to the initial cloud formation stages and the development of precipitation through giant CCN and IN processes" (Möhler *et al.* 2005, 2006). In an early overview paper, the authors have called for a wide-spectrum effort to understand the cloud-formative role of biological agents, through a combination of field study, laboratory experiments and modelling.

Some of the most recent research into biological agent activity has led back to the role of *P. syringae*, which appears to be a rock star (my designation) not only in its microbial class (Christner *et al.* 2008a, 2008b) but among ice nucleators of all types. As a class, biological agents have been found to be the most efficient catalysts for atmospheric ice formation across a range of relatively warm temperatures (warmer than –10 °C) – a discovery of potentially immense import in a warming world. For another, of all the known biological agents, *P. syringae* has been found in the greatest abundance, as well as in the widest distribution in many parts of the world. Since current ability to study the concentration of ice nuclei in the atmosphere is extremely limited, rain and snow samples on land have served as proxies for understanding dispersion and concentration modes and as the basis for predictive modelling. In the case of *P. syringae*, its concentration in particle suspension in rain and snow samples obtained in Antarctica, Louisiana, Montana (Christner *et al.* 2008a, 2008b), the French Alps (Amato *et al*. 2007), the Yukon Territory, and Alberta, Canada (Vali 1971), have dominated all other ice nucleation types, though seasonal differences have obtained. The dominance of *P. syringae* as an ice nucleator has been found despite ecosystem differences, moisture source differences, and differences in air mass trajectories (Christner *et al.* 2008a, 2008b). It has been concluded that biological agents have a "ubiquitous" dispersal (Finlay and Clarke 1999). This is consistent with the highly efficient dispersal properties of *P. syringae*.

Given the routinely inimical treatment within agronomy of *P. syringae* and other biological agents that similarly invade host plants, there are serious choices coming along in the policy realm. As David Sands observes, it behoves us now to understand the relationship between the 'tended' and the unintended consequences of our dealings with earth's interdependent systems.[7] Taking in hand the kinds of questions that a fully systemic approach to the hydrological cycle raises for policy by deploying what is already known about *P. syringae* as an ice-nucleating agent creates a compelling probe. After all, it has been consistently demonstrated that when *P. syringae* is not behaving as a plant pathogen it is – provocatively – leading "other lives" (Morris *et al.* 2007).

Unlike climate change, which is mired in political disadvantage and difficult to test by modest means, the relationship of biological ice nucleators to plant propagation, to bactericidal agents, to wind currents, to tree canopy loss and to soil degradation may lie within relatively easy grasp, though important unanswered questions require the use of sophisticated modelling and other relatively expensive techniques.

What follows in this essay are some of my initial thoughts about what it might mean to take bioprecipitation theory on a tour within the policy realm. Although I assemble all of my ideas except the final one[8] under a meditative canopy, it should be clear which are the more tentative and which are not. Of special interest, even though necessarily tentative, may be my attempt to target improvements in the integration of land use and water policy so that these resource expenditures become sensitive to the incubation, growth, and circumnavigation of the microbiota that may serve a critical function within the earth's hydrological cycle by instigating the production of rain.

Meditations

(1) The field of bioprecipitation got stopped early in its tracks when funding dried up. It did not gain momentum again for almost 30 years. Today, it faces continuing funding hurdles in the US, in that the multidisciplinary, highly collaborative research that currently drives the field transcends the conventions of traditional, agency-authorized intradisciplinary grant review. For work of this kind to achieve its research targets, some methods of adjustment within the grant review process will need to be found. Without these, the US-based research will need to go beggaring, except in its most modest forms, for investment by foreign governments. But foreign public investment is spread among countries and fields. Forging funding linkages can skew both priorities and temporal attachments among internationally dispersed teams, causing misalignments and delays. This is not the optimal way for the research to proceed.

(2) One area of potential research involves the genetic tagging of individual bacterial cells so that their terrestrial and atmospheric trajectories can be tracked.[9] Given the vastness of distances that could be involved and the plethora of inorganic as well as non-bacterial agents that are known to function as ice nucleators, it is plausible to assume that this line of experimentation could pick up only local and specific regional effects, rather than general ones.[10] But for genetic tracking to make possible more localized understandings of atmospheric patterns that affect when and where biota move within the hydrocyclical stream could be of great importance. Learning the influence and flight paths, for example, of rainforest biota – vast organic empires that seem highly identified with and are potentially responsible for local and regional precipitation systems and events – should carry powerful allure.

As of this time, certain countries within South America are accusing Brazil of land use policies in the Amazonian rain forest – especially deforestation – that they claim engender negative effects on rainfall patterns to the south. Improving the knowledge base at the root of this simmering international crisis could lead to responsibility being rightly assigned and remedial measures being undertaken if necessary to maintain sustainable precipitation yields. This is but one example of the work to be done.

(3) Common land use activities that aim at the eradication of pathogenic organisms such as *P. syringae* may need to be significantly re-examined for their hydrological impacts. Cost-benefit analysis comes to mind, should the field prove up. There follow some illustrative prospects for pursuit.

- Educational outreach should be instigated to instil a willingness on the part of agriculturalists world-wide to suspend attempts to eradicate *P. syringae* and other biological ice nucleators once they become securely identified as such. This would entail a significant change in conventional agricultural norms.[11]
- Experimental plantings of crops that currently attract *P. syringae* should be installed to try to establish peak atmospheric biological agent loads, assuming these can be parameterized. This could be accomplished through programmes that subsidize the development of pathogenic seed coatings, followed by experimental plantings on public lands.[12] Or, large experimental tracts could be planted with 'sacrificial' crops (my term), such as tomato and bean cultivars, to serve as hosts in specially prepared and tended arid regions where commercial and residential agriculture do not compete.[13]
- The regulatory approval of crops genetically engineered for immunity to herbicides and pesticides may require examination through the lens of biological agent-related effects. It is currently predicted that newly engineered crops bearing pesticide immunity will increase the use of such eradicants (Pollack 2012, pp. B1, B5). This could engender severe consequences for local and regional populations of phytopathogenic biological agents, such as *P. syringae*. The regulatory integration of any research that may demonstrate this threat should be pursued.
- Dissuasion and even some levels and amounts of interdiction may need to be undertaken, through educational as well as regulatory means, of biotic habitat destruction through such rife practices as suburban commercial and residential clear-cutting; exurban deforestation; urban and suburban irrigation quotas not appropriately calibrated to tree canopy maintenance, leading

to enhanced fire risk; and wetlands infill. The depredatory treatment of public financing for national and state parks, which can give onto inadequate maintenance, park closings, and eventual canopy loss should be reversed and adequate budgets for these essential public goods restored. It is possible that immense green belts or other natural areas will need to be designed to compensate for the microbiotic losses that may be pulverizing or otherwise radically redistributing atmospheric biological agent activity on account of the land use decisions that are routinely made on the basis of conventional policy modes.

- A decisive suppression should take place of the current recrudescence of the Sagebrush Rebellion – a demand, cast in legislative terms, by a coalition of political groups, (eerily) once a generation, that is designed to force the transfer to the states of the public lands held by the federal government. The movement is gathering force through state legislative activity in the US as of the time of this publication – too soon for a case on behalf of bioprecipitation to weigh in, but not too early for the potential effects of the massive Western land sales contemplated in the legislation to be opposed on account of their potentially devastating effects on drought and desertification in a region increasingly prone to these (Trueblood 1980, H.B. 148 [Utah], S.B. 1332 [Arizona]).
- Serious study should be undertaken of the potential for microbiotic loss through the destruction of viable tree canopy in the public parks on account of park closings, with concomitant losses of habitat maintenance programmes. Associated with this are soil degradation and the destruction of canopic habitats, in the event that public parks were to be sold for private development (deBuys 2011, Farrar 2012, *Trends in State Funding of Parks and Recreation* 2011).

It might be useful to conclude this essay with a more extended note than these tightly bundled 'meditations' are able to provide, one that regards a very long-term matter of acrimonious debate connected to the management of the federal public lands. I offer it as an ongoing reminder that drought and desertification are problems that do not attach, of a sudden, only to the twenty-first century, or just to recent climate change fears. In the case of the public lands, they have been a severely disabling problem for a much more protracted time, yielding the administrative law analogue, it seems, of the mythic Gordian knot. The problem involves chronic over-grazing on these lands. The need for revegetation is acute. This has long been recognized. But it has been and continues to be essentially ignored.

At some point, perhaps the need for a very large habitat for *Pseudomonas syringae* will become the public-policy sword that cuts the Gordian knot by furnishing a game-changing argument about the need to conserve the bioprecipitation potential of undeveloped vegetated land masses – an incalculably valuable asset that far outweighs what any other economic use could provide. The final section, below, outlines this claim.

Public policy now: an opportunity to refocus the over-grazing debate

There may be a multiplicity of unintended ways that bacterial pathogens are being excluded from their timeless propagation haunts, whether on and within agricultural crops subjected to bactericides; in previously uncultivated, now built-up areas; or in politically endangered tree canopies. As 'ubiquitous' as bacteria are commonly considered, colony size may require a critical mass, and mass may function as a crucial variable in the production of efficacy when biological agents are in the clouds.

Assuming that cumulative eradication may become a concern, the reclamation of very large land tracts to invite bacterial self-propagation would seem a desirable end. Perhaps it may prove to be a necessary one, if the aggregative destruction of ice-nucleating bacteria were demonstrated to be a negative influence on the propagation of rain. In advance of that proof, we may engage in the present full-blown strategy of doing nothing, or we may choose to experiment with solicitations toward the natural order for the production of rain. A bold venture, and the single most efficient change in land use policy, would be to effectuate a change in the use of public lands. Approximately one-third of the land mass of the United States is owned as public land. Of this, the vast majority is found in the western states. Of this western land, most is owned by the federal government for reasons pertaining to grants, cessions and purchases at the founding and during the first half of the nineteenth century (Gates 1968).

Of these federally administered lands, many millions of hectares constitute a part of what is known as the 'public domain', the subset of public lands not committed to a specific purpose (as are, for example, the national parks). These lands are required under federal law to be administered and maintained, primarily by federal agencies, for the public's benefit in ways that are statutorily prescribed, the age of many of the statutes within this skein giving rise to the view that they are the "lords of yesterday" (Wilkerson 1992).

A chronic source of political conflict in regard to this vast swath of the public domain involves over-grazing. There has been a persistent debate about the federal tolerance of over-grazing that has rocked back and forth across its contested factual predicates for well over a century. During that extraordinary span, the relevant analysis has, on one side – the conservationist side – become ever more factually refined. But this has hardly moved the dial in favour of a major public policy change. In fact, it has not moved the dial, in substantive terms, at all. (For a noteworthy example of a private contribution toward policy change involving federal grazing permits, see Carey 2011.) The problem has been described thusly:

> Few natural resources better illustrate the challenges for natural resource law and policy than our nation's public rangelands. It is no coincidence that grazing provided the archetype for Garrett Hardin's tragedy of the commons nor that it has served as the classic example of agency capture. The current debate over rangeland management also provides a fascinating instance of environmental aspirations butting heads with longstanding tradition, culture and reliance interests. (Rasband *et al.* 2004, p. 880)

The story begins not with aspirations or traditions but with law. Due to environmental degradation, the tragedy of the commons in respect to over-grazing became such a full-blown problem by the early twentieth century that a major piece of statutory architecture was put in place to try to control it. The central pillar of the regulatory scheme – still the central pillar today – was the turn to a permitting system administered under federal authority (the 1934 Taylor Grazing Act, hereafter TGA). These standards were echoed in a subsequent statute that now serves as the comprehensive management scheme for federal lands (the 1976 Federal Land Policy and Management Act, hereafter FLPMA).

The federal regulatory regime that controls the destiny of millions of acres of the western public domain was, from the start, the product of a bifurcated scheme of entitlements. On the one hand, the TGA and, later, the FLPMA have insisted that grazing on public lands is not a right but a privilege (TGA sections 315(b), 316) and that the permits and leases under which grazing has statutorily taken place do not confer any property rights to the lands themselves. Nevertheless, the permits and leases have run for generations – not only of cattle but of people who have made multi-generational ranching on these lands into an iconic way of life that is bound up with the history and traditions of the American West.

These permits have functioned, unlike, for example, intellectual property protection, so as to confer their value over an indefinite life, much in the manner of Anglo-American land titles, the traditional paradigm of property rights themselves. When the government buys out permits to transfer or to retire them – the latter, a stratagem that has begun to foster more active conservation of land and water than existed before – the permit-holders are entitled to gain compensation under the federal constitution's takings clause for the value of the benefits that they have lost – a clear example of privilege transmogrified into right.

The TGA and the FLPMA do not mandate that all land within the public domain has to be put to work for grazing or for any other purpose. Rather, the two agencies responsible for managing the lands are required to look to "multiple uses" and "sustained yield" (FLPMA sect. 1732(a)). Because of the entrenched nature of cattle-raising on these lands, however, shifting to other uses has not proven easy to implement or maintain, particularly when competing uses are not compatible with the needs of cattle or the desires of the politically influential ranchers who own them. The authority of the two agencies is derived from the land management right granted to Congress under the property clause of the US Constitution (Art. IV, sect. 3, cl. 2). It includes the right to impose a regulatory carapace over the lands. Its terms include the requirements that "grazing use shall not exceed the livestock carrying capacity of the allotments" and that uses shall not impair watershed function, riparian habitat, water quality or wildlife habitat (FLPMA sections 4130.3-1(a), 4180.1, 4180.2(c)).

Beyond cavil, all of those damaging excesses have become chronic features of the grossly impaired landscape. What is most deeply problematic about cattle-raising, without reference to the "carrying capacity" of land, is that, more than many types of heavy, roaming animals, such as bison, cattle strip away vegetation in a manner that discourages regrowth and compound this problem by compacting the earth. A rival to cattle-raising on federal lands has been the development of recreational activities such as hiking, camping, hunting, fishing and water-craft use. Licenses and admissions charges for these activities have already demonstrated that they are more extensive sources of federal revenue than is cattle-raising. But the development of several of these uses has been impeded by the degraded state of the resources that cattle have polluted or stamped down (Rasband *et al.* 2004). Even with cost-benefit analysis clearly on recreation's side, the lessening of grazing's hold has been hard to effect.

The authors of a major environmental casebook write: "An important environmental concern related to grazing is desertification, [which] refers to prolonged abuse of land that weakens its ability to support plant growth through loss of soil productivity, increased soil deterioration, and loss of biodiversity. Overgrazing . . . is one of the prime contributors to desertification" (Rasband *et al.* 2004, p. 891). The authors of a major report on these conditions have titled their work *Welfare Ranching: The Subsidized Destruction of the American West* (Wuerthner and Matteson 2002). In its dedication, they decry "the use of America's public lands as private feedlots" (frontispiece, unpaginated). The tenor of the book is captured by this fragment from a pungently-worded speech that concludes: "Subsidized Western range beef is a trivial item in the national beef economy. If all of our 31,000 Western public-ranchers quit tomorrow, we'd never even notice" (p. 60). But these ranchers are not quitting en masse. As long as they are determined to remain, the relevant agencies and Congress seem to lack the political will to end public grazing. And the desertification of public lands in the West continues on.

The research question that bioprecipitation brings to bear is whether the process of desertification could be reversed, with or without present grazing patterns in place. There are reasons to suppose that soil degradation and concomitant flora destruction organically sponsor more of the same. Losses of soil and soil nutrients foster a lack of plant growth. By introducing test-site plantings that would be avoided by cattle because of briars, thorns, or taste, it could be cost-efficient to discover whether bacteria would treat these as hosts.[14] Under this hypothesis, the desire, manifested through policy change, to oppose bacterial-pathogenic habitat destruction through over-grazing could become the game-changer within the politics of endless debate over the present and the future of Western public lands. Under newly devised conditions, some grazing could go on; but so could host-plant propagation that could serve as rehabilitated or newly-constructed microbial habitat.

Conclusion

This essay is funded by the claim that the formation of rain may be linked to the prolificacy of plant pathogens, and that this missing piece of knowledge could be fundamental to water conservation and to land use policy reform. While the theory of bioprecipitation has taken on the contours of a settled account as to its chief finding – that bacteria serve as biological ice nucleators – my attempts to draw significance from this finding have occasioned what are only early thought experiments. Bioprecipitation research has not yet crossed the thresholds of land use or water policy studies, even as a matter of knowledge. I hope to invite vigorous engagement across these frontiers.

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Responsibility for errors of fact or judgment is my own.

Notes

1. The term was coined by Professor David Sands in 1978 (Christner 2012).
2. The most common terminological variants are 'ice nucleation active' (INA) and 'biological ice nucleators' (BIN).
3. Telephone interview with Professor Brent C. Christner, August 2012. Notes on file with the author.
4. What would it mean to 'kill' 'the' rain? Could the eradication of a bacterial pathogen from a particular place – or from a multitude of places – have an inhibitory effect on the formation of rain? The answer is, first, not *all* rain: Even a highly proficient variety of ice nucleator is but one among many kinds, as was discussed in the text. Then, too, anything that fails to live, due to its prior inhibition, cannot, of course, be *killed*. But precipitation could be denied its potential for development, at least at some times and in some places, if one of the atmosphere's best-performing ice nucleators, let us say, should get driven from its earthly haunts

in tree canopies, due to clear-cutting and deforestation; among crops, where it gets eradicated or otherwise inhibited; and in and on the ground, where soils get consolidated so forcefully that they can no longer retain moisture or support life. Could the ferocious consolidation of precipitation that has recently been experienced in several regions of the world be causally related to changes in the earthly and sky-bound concentrations and dispersal patterns of CCN- and IN-active biological agents? This idea is already under study, if more tightly conceived than in my general formulation, in relation to desertification and drought. As noted in the text, the study of dynamic cloud systems is extremely complex. Just the relation of cloud chemistry to rising temperatures has been described as 'an enigma' (Gillis 2012, pp. A1, A14). And current climate models are considered to be better at predicting temperature than precipitation (see, e.g., Gertner 2007, p. 74). Gaps such as these in present knowledge leave room for the bioprecipitation hypothesis to roam and for untested further hypotheses concerning distributive gains and losses in precipitation potential linked to microbial massing and other factors to enter.

5. *P. syringae* received sustained research attention, therefore, as an aggressive and successful pathogen responsible for basal kernel blight in respect to barley (Braun-Kiewnick *et al.* 2000); as a principal causal agent of halo blight in many bean cultivars (Bozkurt and Soylu 2011); as a prolific cause of bacterial shoot blight in tea plants, widely infecting them in tea-growing countries such as Japan (Tomihama *et al.* 2009); and as an antagonist of tomato plants, on which it causes a blight called bacterial speck across the world (see e.g. Bashan and de-Bashan 2002a, 2002b).
6. Telephone interview by the author of Professor David Sands, 24 September 2011. Notes on file with the author.
7. Telephone interview by the author of Professor David Sands, 24 September 2011. Notes on file with the author.
8. I break out for extended treatment the perennial public policy debate regarding the over-grazing of the public lands in the final section of the paper.
9. Personal interview of the author with Professor David Sands, 11 January 2012. In Professor Sands's view, genetic tagging is not a distant prospect but a current opportunity awaiting funding for research.
10. Email communication, Professor Cindy E. Morris to Jane Cohen, 19 September 2011. On file with the author.
11. Professor Morris calls on her students to imagine asking a farmer "which situation is preferable: a year with no rain and no plant disease or a year with some rain and some disease. Which of these two options would she or he choose?" (Morris 2011, email communication, see Note 10). According to Professor Sands, crop loss to *P. syringae* amounts to no more than 5% a year. Telephone conversation with the author, 24 September 2011. Notes on file with the author.
12. Professor Sands included this idea in a TED talk given in April, 2012 – one of the three popular introductions to bioprecipitation published or broadcast that month (Sands 2012).
13. In an earlier version of this paper, presented at IWRA World Water Congress XIV, Porto Galinhas, Brazil, September 2011, and published in its proceedings on the World Wide Web, I more fully elaborated the idea of sacrificial cropping. Manuscript on file with the author available via email transmission on request.
14. David Sands has proposed this experiment. Personal interview of the author with Professor David Sands, 12 January 2012. Notes on file with the author.

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