State of California
Air Resources Board

Response to Notice of Availability of Modified Text and Availability of Additional Documents Released on July 20, 2009

DECLARATION OF BRUCE E. DALE, Ph.D.

I, Bruce E. Dale, declare as follows:

1. I am a scientist with expertise and training in the study of biofuels. I am a Professor in the Department of Chemical Engineering and Materials Science at Michigan State University and Associate Director of the Office of Biobased Technologies at the University. I have a Bachelors (summa cum laude) and a Masters degrees in chemical engineering from the University of Arizona. I received my doctorate from Purdue University, also in chemical engineering, in 1979.

2. I have over 30 years experience in the study of biofuels derived from non-food (or cellulosic) biomass. For the past 8 years I have used life cycle analysis (or "LCA") to understand and improve the environmental performance of biofuels. I have published more than 100 papers in peer-reviewed journals on the subject of biofuels. I served as Co-Chair of the National Research Council Committee on Biobased Industrial Products: National Research and Commercialization Priorities (1994-1997). The National Research Council (NRC) is operated by the National Academy of Sciences to provide high level technical advice to the US government. In 1999-2000 I participated on another NRC panel named "Review of the Research Strategy for Biomass-Derived Transportation Fuels" National Research Council, Washington, D.C. In addition, I have given invited testimony to both Houses of Congress on multiple occasions. My resume is attached to this Declaration as Exhibit A.

3. This Declaration has four parts. Part 1 provides background on the approach taken by the California Air Resources Board (CARB) in the low-carbon fuel standard ("LCFS") rulemaking to the analysis of the emissions impacts of biofuels. Part 2 examines CARB's application of a specific set of models to the task of predicting those emissions impacts. Part 3 examines other relevant emissions impacts that are important, from a scientific basis, in the LCFS rulemaking. Part 4 examines the consistency of CARB's approach to the emissions impact of biofuels with other environmental and economic goals. The papers to which I refer that have not been included as Exhibits to the Comments of Growth Energy are being submitted with this Declaration.

1. Background

4. Life cycle analysis (LCA) is an internationally recognized and generally accepted method to account for the environmental impacts of products and processes. The purpose of LCA is to identify the most environmentally-significant inputs to a particular product so that these can be benchmarked and improved. Most LCA to date has been supply chain oriented, or "attributional" LCA, aimed at understanding the direct or actual life cycle environmental impacts

of specific products. The International Standards Organization (ISO) 14040 standards apply to this type of LCA.

5. Numerous attributional, or supply chain, LCA studies (some of them done by my research group) have shown that biofuels such as corn ethanol, cellulosic ethanol and biodiesel have very favorable life cycle greenhouse gas ("GHG") emissions. The use of biofuels in a given vehicle fleet or group of engines does indeed reduce GHG emissions compared to operation of the vehicle fleet or engine group on gasoline or diesel fuel without biofuels

6. Attributional LCA must be compared with another type of LCA which has appeared in recent years and which is often called "consequential" LCA. Consequential LCA seeks to understand the economy-wide environmental impacts of products and processes. Consequential LCA is not limited to the supply chain of the actual product or process being examined. Instead, it attempts to capture, through price and other relationships, all of the effects a particular product might have throughout the global economy. For obvious reasons, predicting the ripple effects of a particular product throughout the global economy is extremely difficult to do. This type of LCA is not well-developed and there are no internationally-recognized or generally accepted standards for its use.

7. In its analysis of biofuels, CARB is applying consequential analysis to biofuels, and attributional analysis to other fuels. CARB's theory is that owing to indirect land use change, or iLUC, some biofuels actually have very poor GHG footprints and actually are worse than petroleum fuels. iLUC is only one possible component of a consequential LCA. Many other components of a consequential LCA are possible, and some of these are outlined below. CARB has largely ignored other possible consequential LCA components, except for iLUC.

8. Under the theory, iLUC would occur when the world agricultural system reacts, through the signal of increased prices, to replace the agricultural commodities (corn, wheat, sugar, etc.) that have been converted to biofuels and which are no longer available for traditional uses. Hypothetically, new land might need to be cleared to replace these commodities and this land clearing event could release large amounts of greenhouse gases, for example, by burning tropical rainforests. Therefore, any factor which causes agricultural prices to rise can in principle "cause" iLUC.

9. Biofuels, of course, should not escape responsibility for the GHGs released in their own supply chains, including land use change (*e.g.*, by clearing forests to plant biofuel crops). iLUC is something very different. GHG emissions from iLUC are not part of the biofuel supply chain. Instead, they are part *of another product's supply chain* that is being proposed for inclusion in the biofuel supply chain. To say the least, the chain of causation becomes quite attenuated and fragile.

10. The theoretical basis for CARB's analysis is highly suspect. CARB assumes that agricultural expansion is the *cause* of land use change around the world, particularly in the tropical rainforests where the carbon stocks are large. A significant body of scholarly work has looked at the driving forces for land use change in tropical areas. In the work by Geist, Lambin and coworkers, evaluating land use change in the tropics, it was established that only in about four percent of the cases studied was agricultural expansion the primary driver of land use

change. Much more often, timber harvesting (legal and illegal) and infrastructure development (*e.g.*, roads, bridges and dams) were found to be the primary drivers of land use change. Agricultural expansion was a *result* of these other causes and followed them. Therefore in the large majority of actual cases of land use change, agricultural expansion is not a cause of these changes, it is a result of other driving forces.

11. In sum, the literature does not support CARB's assumption that observed land use change in the world was caused by agricultural expansion and therefore it incorrectly attributes to biofuels the cause of land use change. CARB has not examined and discussed the body of scholarly work on the causes of land use change in its regulatory support materials, and that work completely undercuts the theoretical basis for CARB's application of the iLUC concept in this regulatory process.

2. Application of the GTAP Models

12. Despite the lack any empirical basis to support its theory, CARB has used a suite of models, based on work by the Global Trade Analysis Project ("GTAP") to arrive at a fixed point value for the impact of a decision to produce biofuels on GHG emissions, expressed in grams of carbon dioxide equivalent emissions per megajoule of energy ("CO2e/MJ"). This is akin to using a particular model that tries to predict changes in the global climate to set the emissions limits for a petroleum refinery or power plant, notwithstanding the fact that the impact of any particular quantity of GHG emissions from the refinery or power plant on the global climate depends on many other factors, and that the relationship between the release of that quantity of emissions and global temperatures is poorly understood. I am aware of no precedent in the field of biofuels regulation for the use of an untested consequential LCA to establish specific, fixed-value standards like those included in CARB's low-carbon fuel standard.

13. The GTAP is a network of researchers who make their models available to governmental bodies to predict, in broad strokes, how one policy would compare to another policy (such as free trade policy versus a protectionist policy) using some metric of interest. Thus by design, GTAP only considers one driver (eg, one policy change) at a time. This is in stark contrast to the real world in which multiple drivers interact with each other. The GTAP model is non-dynamic and has obtained acceptance only as a method of comparing two or more policy options against a metric of concern or interest. GTAP was never designed for, and *has never been demonstrated to be appropriate for*, the uses to which CARB is putting it.

14. However useful GTAP might be for the original purposes for which it was designed (comparing the effects of different agricultural policies), it has a number of features that make it unsuitable for the task CARB has asked it to fulfill. For example, model inputs and relationships in the real world are synergistic, dynamic and interact with each other; they are not static as GTAP treats them. GTAP does not account for technological change, which is the biggest innovation driver of all. GTAP does not take into account approximately 1 billion acres of abandoned agricultural land in the world. (Campbell, et al, 2009, *Environmental Science and Technology* "The Global Potential of Bioenergy on Abandoned Agricultural Land") Finally, as noted above, GTAP deals only with single factor causation. Because of this, some outcomes of the GTAP model that are viewed as model predictions are actually due to its structure. They are in essence "forced" by the model itself and are not real outcomes of the system being modeled.

15. To my knowledge, prior to this rulemaking there has never been an attempt to use or adapt the models maintained by the GTAP network to predict the land-use change theorized to result from a decision to use biofuels. The only "peer review" of the use of the GTAP models for this purpose was that conducted for CARB in this regulatory proceeding.

16. As the custodians of the GTAP models have acknowledged, there is no actual cause and effect relationship between the decision to produce biofuels and the hypothetical release of greenhouse gases somewhere else in the world. All of the hypothetical linkages are due to economic and policy factors. These must be modeled since no actual supply chain exists for which data can be accumulated. The chosen model is sometimes called GTAP6BIO-AEZ. The scientific community has not generally accepted that model, or any other similar model based on the work of GTAP, as a method for predicting iLUC.

(a) Empirical Evaluation

17. As an initial matter, it is important to recognize that there is no scientific basis for applying consequential analysis to biofuels The scientific method relies on the ability to test a hypothesis or theory to determine whether it is true or not. In fact, the best theories are those which are most easily proven false. CARB has not attempted to test its theory that increased use of biofuels will increase GHG emissions because that increase will result in land-use changes that will in turn increase those emissions. CARB has not explained how such testing could be conducted. In particular, CARB *has not tried to falsify* its theory that increases in agricultural prices lead to deforestation. (I provide below some preliminary evidence showing that the iLUC theory is indeed false.) Assertions and opinions which cannot be tested and falsified are, but their very nature, unscientific. To maintain scientific integrity, CARB's emphasis should be focused on testing its predictions to determine if they are wrong, not on trying to uphold its predictions in the face of evidence to the contrary.

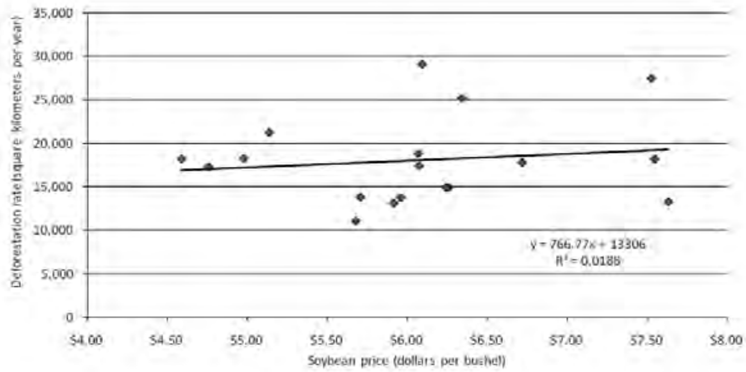
18. Models are sometimes used to predict how a regulation will affect future emissions levels. But those models can be tested by using "back-casting" to determine if they would have correctly predicted past emissions levels. The observed data can be used to assess the predictive power of the model. CARB has not attempted this with respect to GTAP6BIO-AEZ, and to my knowledge no version of the GTAP suite of models has ever been used before to try to predict GHG emissions that will result from a decision to use biofuels.

19. The failure to test GTAP6BIO-AEZ is a very serious shortfall from sound scientific practice. The suite of models applied by CARB links at least four cause-and-effect models or sets of assumed relationships: (i) ethanol demand to corn price, (ii) corn price to corn or soybean supply, (iii) corn or soybean supply to land use change, and (iv) land use change to greenhouse gas emissions. Embedded in the last assumed relationship, which generates the final result, are at least two components: (i) greenhouse gas emissions at the time of land conversion, and (ii) greenhouse gas emissions occurring during post-conversion management. Greenhouse gas emissions at the time of conversion in turn depend in large part on the fate of the above-ground carbon. If trees have been removed, for example, it is very important from a life cycle perspective to know or predict accurately whether the trees will be used for lumber, to make paper or other products, etc, or if the trees have simply been burned without producing useful products. It is likewise critical to understand what type of land (eg, grassland vs. forest) was

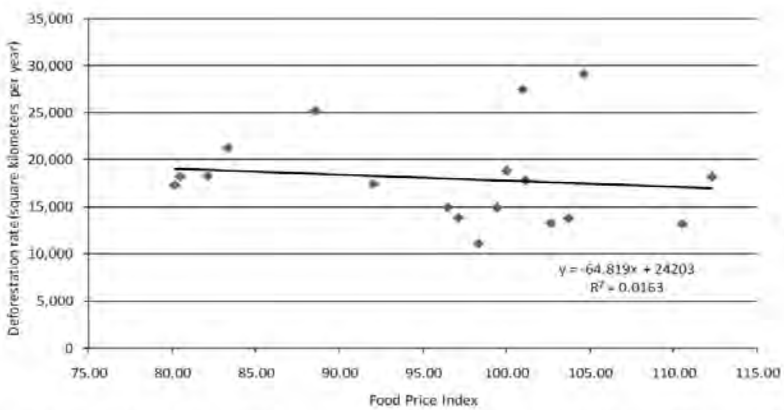
converted and how that land was managed after conversion. Work from my own laboratory has shown that for the case of grasslands converted to biofuel crops and then managed using carbon-conserving tillage practices, the assumed "carbon debt" due to biofuels nearly disappears and that for forest conversion is greatly reduced. (H. Kim, S. Kim and B. Dale, *Environmental Science and Technology*, "Biofuels, Land Use Change and Greenhouse Gas Emissions: Some Unexplored Variables" 2009. Vol. 43 (3) pgs. 961-967)

20. There are important uncertainties in each of the five major stages of the analysis, which the authors of GTAP readily admit. This inevitably leads to amplified uncertainties in the final results, or what is called a "propagation of errors". This is one reason why it is surprising, and not consistent with the real capabilities of the GTAP models, that CARB has attempted to use those models to determine a single-point value for the carbon intensity of a decision to use biofuels. No scientific measurement in the real world *ever results in a single point value, the result is always a range of values*. The authors of GTAP admit it, but CARB ignores this fundamental scientific reality. Not only has CARB ignored the uncertainty in each of the five major stages of the analysis, it has grossly ignored how these stage-wise uncertainties will produce greatly amplified uncertainty in the final estimates. This is simply unacceptable scientific procedure.

21. To the extent the predictive accuracy of the GTAP models and CARB's assumptions for this purpose can be tested empirically, those models and assumptions fail. Fundamentally, iLUC (as embodied in CARB's own assumptions and use of GTAP) predicts that increases in prices for commodities that can be used for both biofuels and human and animal nutrition will lead to increased land conversion. Dr. Robert Brown of Iowa State University has provided a simple test. Dr. Brown has assembled data showing the relationship between soybean prices and commodity food prices versus the deforestation rate in the Amazonian rainforest of Brazil. The deforestation rate data are derived from the United Nations Food and Agriculture Organization (FAO) and the soybean price and the commodity food price index from Index Mundi. Both of these sources are considered reliable sources of information for such data and are relied on by scientists like myself. Simply put, there is no statistically significant relationship between either soybean prices or world food prices and deforestation rates in the Amazon. Thus CARB's analysis fails this key test. (Both figures below are courtesy of Dr. Brown.)



There is no correlation between the price of soybeans and the deforestation rate in the Amazonian rainforest of Brazil. The solid line is a "best fit" of the data, which shows a small positive linear correlation. However, the regression coefficient (R^2) of 0.0188 indicates virtually no statistically significant correlation (a value of 1.00 is a perfect correlation). Source: United Nations Food and Agriculture Organization (deforestation data) and Index Mundi (soybean price data).



There is no correlation between the commodity food price index and the deforestation rate in the Amazonian rainforest of Brazil. The solid line is a "best fit" of the data, which shows a small negative linear correlation. However, the regression coefficient (R^2) of 0.0163 indicates virtually no statistically significant correlation (a value of 1.00 is a perfect correlation). Source: United Nations Food and Agriculture Organization (deforestation data) and Index Mundi (food price index).

22. The work by Brown shows that the models are not correct in predicting that there is a relationship between agricultural commodity prices and the rate of land clearing in the tropics, for example in the Amazon. Likewise a relationship should exist between food prices and the rate of land clearing. Neither is true, as shown above. If CARB's approach is unable to predict the past trends in land use change, there is absolutely no reason to believe it will be able to predict future trends. In other words, if CARB's approach cannot accurately "back cast" there is no reason to believe it will be able to forecast accurately.

(b) Application of generally accepted criteria for LCA to CARB's iLUC analysis

23. To the extent the application of the GTAP models to CARB's regulatory purposes is to be assessed according to generally accepted LCA principles, it should conform with the LCA principles promulgated by the International Standards Organization (ISO). According to

ISO, a sound lifecycle analysis must (a) use the most recent, most accurate data possible, (b) ensure transparency, making it easy for others to check the data and modeling, (c) set clear system boundaries and apply them equally across all products, and (d) conduct careful sensitivity analyses.

24. CARB has not used the most recent and accurate data possible in its specially-adapted GTAP models. For example, CARB has not determined what the actual fate of the standing carbon is when the land is supposedly converted to agriculture as a result of demand for biofuels. From an emissions standpoint it is critical to know whether the standing carbon was simply burned or whether it was put to some productive use. Likewise the type of land converted (forest vs. savannah vs. grassland) is a critical part of any calculation. Grasslands and savannah have much less carbon "at risk" than do forests. To make valid predictions of iLUC, we need to know what type of land was converted. Further, we need to know how the land was managed following the land conversion event. Carbon conserving practices such as no till or reduce till and cover crops can greatly diminish, or even reverse carbon losses due to the land conversion event. Those are only a few examples. As Lynd and Dale (October 27, 2008 presentation to the Scientific Advisory Board of the Environmental Protection Agency in Washington, DC) have explained, there are over 500 factorial combinations of inputs and assumptions included in the type of predictive modeling that CARB has attempted -- at least eight of which are related to biomass source (sustainable wastes, excess or degraded cropland, integration into new agricultural practices, forests without land conversion, grassland conversion to high productivity biomass, forestland to high productivity biomass, non sustainable agricultural land and sustainable agricultural land) and seven of which are related to biomass fate. CARB has not documented and tested its assumptions for each of those eight types of biomass source and seven types of biomass fate. This is not acceptable as a matter of sound scientific practice. It is not acceptable as a matter of sound life cycle analysis.

25. CARB has also not set clear system boundaries -- both temporal and physical -- and applied them consistently. System boundaries (both physical and temporal) for biofuels and other fuels should be equal or comparable. In CARB's analysis, they are not. CARB compares future biofuels with petroleum fuels in 1999-2005, so the temporal boundaries are not the same. CARB should determine the likely environmental profile of petroleum fuels in the same time period as biofuels. Likewise the physical boundaries are not comparable at all. Among other things, this goes to the iLUC issue discussed above and below. Indirect effects are assessed to biofuels in which all of the economically available land in the world is modeled, but not to petroleum fuels for which only the direct supply chain effects in a very limited geography are modeled.

26. With respect to transparency, the GTAP models applied here are reportedly complex and difficult to use. It is unclear, for example, whether the CARB "peer reviewers" attempted to and were able, and did in fact, operate GTAP6BIO-AEZ. It is impossible to consider this to have been a thorough peer review if the models were not operated by the peer reviewers.

3. Other Indirect Effects

27. As noted above, sound LCA practice requires the evaluation of environmental impacts of all products and processes under examination. This has clearly not been done in the development of the LCFS regulation. The concept that "the polluter pays" is well understood -- the party who is more directly responsible for an environmental impact is to pay for the damage imputed to its product or process. This is necessary in order to obtain what is judged to be the optimal level of control. Under the iLUC theory, however, quite literally the polluter does not pay in order to obtain an optimal level of control. Under the iLUC theory, the hypothetical decision to clear land for agriculture is not assessed solely (and perhaps not at all) to the agent doing the clearing; rather it is assessed to the biofuel producer who has no control at all over this land clearing decision. (If the party clearing the land also "pays," either through a regulation or some other means, there would be over-control, and potentially huge social-welfare losses in addition to those incurred as a result of the initial application of the iLUC theory.)

28. Moreover, iLUC is only *one* example of indirect effects analysis. iLUC is only one example of an indirect (market, policy or "leakage") effect. Since CARB has applied indirect effects analysis to biofuels, it is thereby obligated to apply indirect effects analysis broadly to all the fuel pathways it is considering. A few such analyses have been suggested above. If CARB does not apply indirect effects analysis broadly to all fuel pathways, it will violate its own principle of being neutral and evenhanded in its treatment of fuel pathways. There is no intellectual or ethical justification for considering some indirect effects and excluding others. To treat all fuels equally, which is CARB's stated policy, CARB must therefore include all indirect effects for all fuel pathways. A few examples will follow.

29. Indirect effects are not supply chain oriented; they are market and policy oriented. Any market effects or any policy effects that can conceivably "cause" GHG release should therefore be included in GHG accounting through indirect effects analysis. For example, U.S. policy since 1945 has been to maintain a military presence in the Persian Gulf to keep the oil flowing. It seems reasonable therefore to "charge" petroleum fuels with the prorated GHG emissions of the U.S. military (and other armed forces) that have kept the oil supply lanes open. CARB's analysis of petroleum fuels does not do this.

30. Another example, even closer to the iLUC case, is that of nickel mining for nickel hydride batteries for electric vehicles (BEVs). The iLUC argument based on market forces is as follows: if someone uses nickel for electrical vehicles then he or she is not only responsible for the supply chain (direct) GHG emissions of that nickel, but also for hypothetical GHG releases due to new nickel mines to replace the nickel going into car batteries. If CARB is not evaluating the indirect effect of nickel mining for BEVs, it is favoring one fuel pathway over another and has violated one of its primary policy principles.

31. As another example, the proponents of the CARB rule from the Northeastern United States have apparently overlooked (or ignored) another indirect effect of increasing the number of BEVs on the roads. If the demand for electricity increases due to increased numbers of BEVS, then some of that incremental electricity demand will be met by coal burning power plants. While the California Public Utility Commission has set "Environmental Performance Standards" for electricity in California, no such rules are in place everywhere else the regulation

may be implemented. For that reason, BEVs will have a terrible GHG footprint and will incur a very large "carbon debt" if the California rule spreads to other States. CARB knows very well that its regulations are likely to be widely adopted by other States. It is disingenuous and misleading to claim otherwise.

32. BEV proponents might argue that the electricity demands of these vehicles can be met from wind, solar or some other low carbon energy source. That is irrelevant. If BEVs cause an increased demand for electricity, then through price signals they should be held responsible for the worst possible outcome for how that electricity might be supplied, just as biofuels have been held responsible for the worst possible outcome in how the increased demand for agricultural products might be met. The worst possible outcome is that the increased electricity demand will be met by burning coal, with its huge resulting GHG impact.

4. Other Considerations

33. Finally, it is important to note the inconsistency of the iLUC regulatory concept with well-accepted national goals and social norms. Any policy action that tends to support farm prices will keep them higher than they would have otherwise been and will lead to iLUC. By that view, all farm support programs are not consistent with CARB's current regulatory approach. Consistency would require CARB to use its police power to end such farm policies. (Taken to its full logical reach, any national or international program to increase the prosperity of rural communities in the U.S. and around the world is misbegotten, because prosperity in the rural sector will "cause" iLUC by price mechanisms.)

34. Any policy action that removes arable land from agricultural production will have the effect of raising agricultural prices and will therefore "cause" iLUC. Therefore the Conservation Reserve Program (CRP) (through which environmentally-sensitive lands are taken out of agricultural production) will "cause" iLUC and should be ended. Similarly, all national and state parks, national monuments, greenbelts, and conserved wetlands, also cause iLUC since they remove land from agricultural production and tend to raise crop prices. Therefore, all of these parks, etc. should be closed and used for agricultural production, or for grazing by animals, to also reduce farm prices. To be consistent, CARB should prohibit importation of fuels from any state or country that practices such land conservation efforts, because these policies reduce the amount of agricultural land in production, raise prices and thereby cause iLUC.

35. CARB assesses the entire environmental "cost" of iLUC against biofuels, in spite of the fact that we use land to provide food, feed, fiber, timber and many other products. We could choose to use less of these other products at any time and thereby relieve pressure on land so that biofuels would not incur any iLUC. Instead, CARB's analysis gives a privileged position regarding GHG emissions to existing uses of land, and penalizes only biofuels. This is contrary to equity, to common sense and to the allocation principle of LCA.

36. Since most human use of land is to provide animal feed, CARB's failure to allocate iLUC among all the drivers of land use change means that CARB's analysis implicitly recognizes animal feed as sustainable and GHG friendly, while biofuels are not. This is neither intellectually nor ethically defensible. It is well known that animal agriculture has a very large GHG footprint, which CARB's analysis implicitly protects by not allocating an appropriate

GHG footprint to animal agriculture in the overall land use change calculation. There is no intellectual justification for pursuing sustainable fuels and ignoring unsustainable animal feeds when these two issues intersect, as they clearly do in this case.

37. CARB has stated that it wishes to encourage so-called "advanced" or "second generation" biofuels derived from cellulosic materials. However, CARB's flawed use of LCA whereby attributional and consequential LCA's are mixed will discourage rather than encourage investment in and deployment of advanced biofuels. If proper LCA analysis can be twisted and manipulated almost at the whim of the analyst as CARB has done here for iLUC (by changing system boundaries, not doing proper allocation, etc.) then no fuel or fuel pathway is safe from politically or ideologically driven analyses that do not abide by international standards, or even by common sense and rational, clear thought.

I declare under penalty of perjury under the laws of the State of California that the foregoing is true and correct.

Executed this 19th day of August, 2009 in Madison, Wisconsin.

Bruce E. Dale, Ph.D.

DECLARATION OF BRUCE E. DALE, Ph.D.

EXHIBIT A

BIOGRAPHICAL DATA

DALE, Bruce E. JANUARY 2009
Distinguished University Professor
Department of Chemical Engineering and Materials Science

Address:
Department of Chemical Engineering
3247 Engineering Building
Michigan State University
East Lansing, Michigan 48824-1226
Phone: 517/353-6777
FAX: 517/432-1105
E-Mail: bdale@egr.msu.edu

BACKGROUND

Birthdate: June 13, 1950
Citizenship: U.S.A.
Birthplace: Ely, Nevada, USA
Marital Status: Married
Security Clearance: None
Number of children: Five

PROFESSIONAL INTERESTS

Utilization of cellulose and other renewable resources, biobased industrial products, rate-limiting processes in biological systems, bioremediation, modeling of integrated economic/environmental systems, life cycle analysis, ecological engineering.

EDUCATION

B.S. University of Arizona, Chemical Engineering, 1974 (with highest distinction)

M.S. University of Arizona, Chemical Engineering, 1976

Ph.D. Purdue University, Chemical Engineering, 1979

EXPERIENCE (Academic, industrial, consulting, other)

Associate Director, Office of Biobased Technologies, Michigan State University, June 2006-present

Professor, Department of Chemical Engineering and Materials Science, Michigan State University, August 2001-present

Acting Chair, Department of Materials Science and Mechanics, Michigan State University, August 2000- August 2001

Adjunct faculty member, Department of Biology, Central Michigan University 1999 - Present

Professor and Chair, Department of Chemical Engineering, Michigan State University, January 1996 – August 2001

Professor, Chemical Engineering and Agricultural Engineering, Texas A&M University, September 1991 - December 1995

Director, Food Protein Research and Development Center, Texas A&M University, August 1991 - November 1993

Director, Engineering Biosciences Research Center, Texas A&M University, May 1990 - December 1995

Associate Professor, Chemical Engineering and Agricultural Engineering, Texas A&M University, August 1988 - May 1991

Professor, Chemical Engineering, Colorado State University, July 1988 - August 1988

Associate Professor, Chemical Engineering, Colorado State University, Fort Collins, Colorado, August 1987 - June 1988

Scientific Advisor, Synergen Corporation, Boulder, Colorado, May 1987 - August 1987

Visiting Scientist, National Bureau of Standards, Boulder, Colorado (Sabbatical Leave), August 1986 - May 1987

Associate Professor, Chemical Engineering Program, Colorado State University, Fort Collins, Colorado (Tenure awarded July 1984), June 1983 - August 1986

Assistant Professor, Chemical Engineering Program, Colorado State University, Fort Collins, Colorado, July 1979 - May 1983

Instructor in Chemical Engineering, Purdue University, Lafayette, Indiana, 1977 (Fall)

Instructor in Chemical Engineering, University of Arizona, Tucson, Arizona, (Phillips Petroleum Fellowship) 1975 – 1976

SOCIETY AND FACULTY MEMBERSHIPS

American Institute of Chemical Engineers
- Food, Pharmaceutical and Bioengineering Division,
American Chemical Society - Division of Microbial and Biochemical Technology

HONORS AND AWARDS

National Merit Scholar
National Honor Scholar
Halliburton Outstanding Young Faculty Award (1982)
Abell Young Faculty Research Award (1984)
Colorado State University Research Foundation Researcher of the Year (1986)
Engineering Dean's Council Award (1987)
Greatest Entropy Award (1988) - Teaching Award Presented by Student Chapter of AIChE at Colorado State University to the Outstanding Professor
Editorial Board, Biotechnology Progress (1989-present)
Editorial Board, Biotechnology and Bioengineering (2002-present)
Editor, Bioresource Technology (1991-1996)
Co-Chair, National Research Council Committee on Biobased Industrial Products: National Research and Commercialization Priorities (1994)
Charles D. Scott Award (1996)
Professor of the Year 2002 Award (MSU Department of Chemical Engineering)
Sterling Hendricks Award Lecture 2007 (highest research prize given by the U. S. Dept. of Agriculture-Agricultural Research Service)
Editor-in-Chief *Biofuels, Bioproducts and Biorefineries.* (2007-present)
Biomass Processing Research Thrust Leader for Great Lakes Bioenergy Research Center (2007-present)
University Distinguished Professor. Michigan State University. (2008-present)
Chair: International Roundtable on Sustainable Biofuels—Greenhouse Gas Section. Sponsored by the Swiss Federal Institute of Technology, Zurich Switzerland. (2008-present)

LANGUAGES

Fluent in Spanish (speaking, reading and writing)

CONSULTING/EXPERT WITNESS EXPERIENCE

Atlantic Richfield Corporation, Dublin, California
Red River Feed Corporation, Casa Grande, Arizona
Adolph Coors Corporation, Golden, Colorado
Saskatchewan Research Council, Saskatchewan, Canada

Tennessee Valley Authority, Muscle Shoals, Alabama
Coors Biotech Products Corporation, Ft. Collins, Colorado
Synergen Corporation, Boulder, Colorado
Solar Energy Research Institute, Golden, Colorado
National Bureau of Standards, Boulder, Colorado
Stearns-Rogers Corporation, Denver, Colorado
Quaker Oats Corporation, Barrington, Illinois
Syntex Corporation, Boulder, Colorado
Abbott Laboratories, Chicago, Illinois
RA Energy, Austin, Texas
Amoco Production Corporation, Farmington, New Mexico
Electrica Integral, S. A. de C. V., Mexico City, Mexico
Boswell and Hallmark, L.L.P, Houston, Texas
Crowley, Marks and Douglas, L.L. P., Houston, Texas
Fleming, Hovenkamp & Grayson, L.L.P., Houston, Texas
Mithoff and Jacks, L.L.P., Austin, Texas
Pohl and Bennett, P.C., Houston, Texas
Munroe and Nobach, P.C., East Lansing, Michigan
DuPont, Inc., Wilmington, Delaware
DiCecco, Fant and Burman, L.L.P., Houston, Texas
Phillips and Akers, P. C. Houston, Texas
MBI, International, Lansing, Michigan
Cargill-Dow Polymers, LLP, Minnetonka, Minnesota
Hatch and Parent, P. C., Santa Barbara, California
DuPont Biobased Materials, Inc., Wilmington, Delaware
Greben and Associates, Santa Barbara, California
Miller, Axline and Sawyer, LLP, Sacramento, California
Genencor, Inc., Beloit, Wisconsin
Cargill, Inc., Minneapolis, Minnesota
Vandeveer Garzia, PC Troy, Michigan
Flowers and Davis, PLLC, Tyler, Texas
McMillan and Shureen, LLP, Santa Rosa, California
Cortner McNaboe Colliau & Elenius, San Francisco, California
Organization for Economic Cooperation and Development, Paris, France
BP North America, Houston, Texas
Mascoma Corporation, Boston, Massachusetts
Edenspace Corporation, Lawrence, Kansas
GM Corporation, Detroit, Michigan
Growth Energy, Sioux Falls, South Dakota
National Biodiesel Board, St. Louis, Missouri
POET, LLC, Sioux Falls, South Dakota
Renewable Fuels Association, Washington, DC

ADDITIONAL FORMAL TRAINING

Short Course "In Situ and On Site Bioremediation" offered by the International Network for Environmental Training, April 22 and 23, 1995, San Diego, California (1.2 CEUs)

Short Course "Groundwater Pollution and Hydrology" offered by the Princeton Course, July 31-August 4, 1995, Orlando, Florida (3.7 CEUs)

PUBLICATIONS

Book Chapters (Refereed)

Dale, B. E. 1991. "Ethanol Production from Cereal Grains." Chapter 24 in Handbook of Cereal Science and Technology, eds. K. J. Lorenz and K. Kulp, Marcel Dekker, Inc., NY.

Dale, B. E. and R. J. Gillies. 1991. "Nuclear Magnetic Resonance Spectroscopy of Dense Cell Populations for Metabolic Studies and Bioreactor Engineering: A Synergistic Partnership" Chapter #5 (pp. 107-119) in Animal Cell Bioreactors, Butterworth-Heineman, Stoneham, Massachusetts eds. C. S. Ho and D. I. C. Wang.

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“Greenhouse Gas Emission Profile of Ethanol Production Under Various Cropping Systems” Seungdo Kim and Bruce E. Dale (presenter). Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. San Francisco, CA Nov. 21, 2003

“Genetic System Development, Metabolic Engineering, Bioenergetics and Kinetics Relevant to Ethanol Production Using Thermophilic Bacteria” Lee. R. Lynd (presenter), Sunil Desai, Mikhail Tyurin, Yiheng Zhang, Yanpin Liu, A. Joe Shaw, Jonathan Mielenz and Bruce E. Dale. Oral Presentation at the 26th Symposium on Biotechnology for Fuels and Chemicals. Chattanooga, Tennessee. May 9-12, 2004.

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"Enzymatic Hydrolysis of Poplar Pretreated by Ammonia Fiber Explosion" Venkatesh Balan (presenter) and Bruce E. Dale, et al. Oral Presentation 183f at the Annual Meeting of the American Institute of Chemical Engineers. Cincinnati, Ohio. October 30-November 4, 2005.

"Enzyme Synergies in the Hydrolysis of AFEX Pretreated Biomass" Shishir P. Chundawat (presenter) and Bruce E. Dale, et al. Oral Presentation 449d at the Annual Meeting of the American Institute of Chemical Engineers. Cincinnati, Ohio. October 30-November 4, 2005.

"Cellulose Nanofibers Extracted from Microcrystalline Cellulose and Corn Stover" Tao Wang (presenter) and Bruce E. Dale, et al. Oral Presentation 336a at the Annual Meeting of the American Institute of Chemical Engineers. Cincinnati, Ohio. October 30-November 4, 2005.

"Separation of Protein from Switchgrass Using Aqueous Ammonia During Biomass Refining" Bryan Bals (presenter) and Bruce E. Dale, et al. Oral Presentation 589a at the Annual Meeting of the American Institute of Chemical Engineers. Cincinnati, Ohio. October 30-November 4, 2005.

"Mature Technology Biorefinery Scenarios Emphasizing Fuels and Power" Mark Laser (presenter) and Bruce E. Dale, et al. Oral Presentation 575a at the Annual Meeting of the American Institute of Chemical Engineers. Cincinnati, Ohio. October 30-November 4, 2005.

"All Biomass is Local: Environmental Impacts of Ethanol Derived from Corn Grain" Bruce E. Dale (presenter) and Seungdo Kim. Oral Presentation 575b at the Annual Meeting of the American Institute of Chemical Engineers. Cincinnati, Ohio. October 30-November 4, 2005.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Oral Presentation at the Biotechnology Industry Organization (BIO) International Convention, Chicago, Illinois. April 10, 2006.

"Comparison of Pretreatment Technologies for Cellulosic Biomass" Bruce E. Dale (presenter). Oral Presentation at the Biotechnology Industry Organization (BIO) International Convention, Chicago, Illinois. April 12, 2006.

"Process Options in AFEX Pretreatment and Fermentation of Rice Straw" Venkatesh Balan (presenter), Shishir Chundawat and Bruce E. Dale. Poster 2-62 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"The Development of a Microplate Technique for Screening Enzyme Mixtures and Synergistic Additives for Hydrolysis of AFEX Treated Lignocellulosic Biomass" Shishir Chundawat (presenter), Venkatesh Balan and Bruce E. Dale. Poster 2-21 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"Extracting Proteins from Switchgrass within an Integrated Biorefinery" Bryan Bals (presenter), Venkatesh Balan and Bruce E. Dale. Poster 2-12 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"Life Cycle Analysis of the AFEX Process in Consideration of Recent Process Improvements" Elizabeth Newton (presenter), Hasan Alizadeh, Bruce E. Dale, Seungdo Kim, Mark Laser and Lee Lynd. Poster 1A-43 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"More than Just Carbon Dioxide: Nitrous Oxide is the Dominant Greenhouse Gas in Corn Based Biofuels and Bioproducts" Bruce E. Dale (presenter) and Seungdo Kim. Oral Presentation STA-02 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"Comparative Sugar Recovery Data from Application of Leading Pretreatment Technologies to Corn Stover and Poplar" Charles E. Wyman (presenter), Bruce E. Dale, Richard T. Elander, Neil Gilkes, Mark T. Holtzapple, Michael R. Ladisch, YY Lee, and Mohammed Moniruzzaman. Oral Presentation 2-05 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"Recent Process Improvements for the Ammonia Fiber Expansion (AFEX) Process and Resulting Reductions in Projected Ethanol Prices" Bruce E. Dale (presenter), Elizabeth Newton, Lee Lynd and Mark Laser. Oral Presentation 2-02 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"Research Challenges and Opportunities for Cellulose Conversion Technology in a Dry Mill Pathway" Michael R. Ladisch (presenter), Wallace Tyner, Nathan Mosier, Michael Cotta, Bruce Dien, Hans Blaschek, Bruce Dale, Brent Shanks and Eugene Peterson. Oral Presentation 2-03 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"Conversion of Cellulose to Glucose using endo-1,4, beta glucanase Enzyme Produced in Transgenic Rice Plants" Hesham Oraby (presenter), Rashid Ahmad, Callista Ranson, Mariam Sticklen, Venkatesh Balan and Bruce E. Dale. Oral Presentation 1B-05 at the 28th Symposium on Biotechnology for Fuels and Chemicals. Nashville, Tennessee. April 30-May 3, 2006.

"The Effect of Chemical Treatments of Corncobs on the Properties of Corncob Reinforced Poly (lactic acid) Composites. Masud S. Huda (presenter), Lawrence T. Drzal, Venkatesh Balan, Bruce E. Dale and Manju Misra. Oral Presentation at the International Degradable Plastics Symposium, Chicago, Illinois, June 14-17, 2006.

"Improving Biomass Conversion by Better Fundamental Understanding of Pretreatments: The Case of Ammonia Fiber Expansion (AFEX)" Bruce Dale (presenter), Venkatesh Balan, Shishir Chundawat, Bryan Bals and Ming Woei Lau. Oral Presentation 672b at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Understanding Enzyme Synergy in AFEX Treated Biomass" Bruce Dale (presenter), Venkatesh Balan and Shishir Chundawat. Oral Presentation 623a at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Concentration of Proteins from Switchgrass and Distillers Grains using Ultrafiltration during Biomass Refining" Bruce Dale (presenter), Bryan Bals, Ming Woei Lau and Venkatesh Balan. Oral Presentation 611b at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Life Cycle Assessment of Integrated Biorefinery: Corn Grain, Corn Stover and Switchgrass" Bruce Dale (presenter), Seungdo Kim, Mark Laser and Lee Lynd. Oral Presentation 595a at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Considering Advanced Biorefineries in Context" Mark Laser (presenter), Shahab Sokhansanj, David Bransby, R. Lance Martin, Haiming Jin, Lee R. Lynd, Eric D. Larson and Bruce E. Dale. Oral Presentation 595b at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"The Effects of AFEX Pretreatment on the Fermentability of Lignocellulosic Hydrolysates Using *E. Coli* KO11" Bruce Dale (presenter), Ming Woei Lau and Venkatesh Balan. Oral Presentation 531c at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Modified AFEX Pretreatment Conditions and Enzymatic Hydrolysis of Poplar" Venkatesh Balan (presenter), Bruce E. Dale and Shishir Chundawat. Oral Presentation 516b at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Comparative Data for Enzymatic Digestion of Corn Stover and Poplar Wood after Pretreatment by Leading Technologies" Charles Wyman (presenter), Bruce E. Dale, Richard T. Elander, Mark T. Holtzapple, Michael R. Ladisch, YY Lee, Mohammed Moniruzzaman and John N. Saddler. Oral Presentation 516a at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California. November 12-17, 2006.

"Energy from Agricultural Biomass: Sustainability Considerations" Bruce E. Dale (presenter) Oral Presentation at the American Association for the Advancement of Science, Annual Meeting, San Francisco, California. February 16, 2007.

"Cellulosic Ethanol and Sustainability: There Is No "Food vs. Fuel Conflict" Bruce E. Dale (presenter). Oral Presentation at the 233rd Annual Meeting of the American Chemical Society, Chicago, Illinois. March 25-29, 2007.

"Designing a New Industry for Sustainability: Life Cycle Analysis for the Emerging Bioeconomy". Bruce E. Dale (presenter) and S. Kim. Oral Presentation at the 233rd Annual Meeting of the American Chemical Society, Chicago, Illinois. March 25-29, 2007.

"Comparison of Crop and Animal Simulation Options to Model an Integrated Biorefinery Using AFEX" E. D. Newton, S. Kim, B. D. Bals, B. E. Dale, M. Laser and L. R. Lynd. Poster Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Technoeconomic Feasibility of Regional Biomass Processing Facilities" J. E. Carolan, B. E. Dale and S. V. Joshi. Oral Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Towards a Fundamental Understanding of Ammonia Fiber Expansion (AFEX) Pretreatment and Its Effect on Enzymatic Hydrolysis and Fermentation" S. P. Chundawat, V. Balan, D. A. Jones, L. D. Sousa, M. W. Lau, and B. E. Dale. Oral Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Improvements in Glucan Conversion in Rice Straw while Producing Valuable Isolates Using Solid State Fermentation and the AFEX Process" V. Balan, S. P. Chundawat, H. Gunter, and B. E. Dale. Poster Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Improving AFEX Pretreatment using Concentrated Aqueous Ammonia" B. D. Bals, H. Alizadeh, D. J. Marshall, E. D. Newton, V. Balan, and B. E. Dale. Poster Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Optimization of Ammonia Fiber Expansion (AFEX) Pretreatment and Enzymatic Hydrolysis of *Miscanthus x giganteus* to Fermentable Sugars" H. Murnen, V. Balan, S. P. Chundawat, B. Bals and B. E. Dale. Poster Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Enzymatic Hydrolysis of AFEX Treated Corn Stover and *Miscanthus* at High Solid Loadings" L. Sousa, V. Balan, S. P. Chundawat, and B. E. Dale. Poster Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Development and Validation of an Automated 96 Well Microplate Hydrolytic Assay for AFEX Treated Lignocellulosics Using Commercial Enzyme Mixtures and Synergistic Fungal Enzymes" S. P. Chundawat, V. Balan, S. Nagendran, H. Gunter, J. D. Walton, and B. E. Dale. Poster Presentation at the 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Comparative Sugar Recovery and Fermentation Data and Economic Projections for

Applications of Leading Pretreatment Technologies to Corn Stover and Poplar" B. Yang, C. Wyman, B. E. Dale, R. T. Elander, M. Holtzapple, M. R. Ladisch, Y. Lee, C. Mitchinson, and J. N. Saddler. Poster Presentation at the 29^{th} Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Overview of Biomass Refining Consortium for Applied Fundamentals and Innovation" C. Wyman, B. E. Dale, R. T. Elander, M. Holtzapple, M. R. Ladisch, Y. Lee, C. Mitchinson, and J. N. Saddler. Poster Presentation at the 29^{th} Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Comparing the Fermentability of Corn Stover Hydrolysate from Ammonia Fiber Expansion and Dilute Acid Pretreatment" M. W. Lau, V. Balan, and B. E. Dale. Poster Presentation at the 29^{th} Symposium on Biotechnology for Fuels and Chemicals. Denver, Colorado. April 29 – May 2, 2007.

"Recent Research Results of the Biomass Refining CAFI" C. Wyman, B. E. Dale, R. T. Elander, M. Holtzapple, M. R. Ladisch, Y. Lee, and J. N. Saddler. Oral Presentation at the BIO International Convention. Boston, Massachusetts. May 8, 2007.

"Sustainability of Biofuel Systems" B. E. Dale and S. Kim. Oral Presentation at the Michigan Bio-Economy Summit. Lansing, Michigan. September 12-13, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" B. E. Dale. Oral Presentation at the Michigan Bio-Economy Summit. Lansing, Michigan. September 12-13, 2007.

"Effect of Nitrogen Fertilizer on the Ethanol Fuel System" S. Kim and B. E. Dale. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Using Regional Biomass Processing to CoProduce Animal Feed and Ethanol from Grasses" B. Bals, H. Murnen, B. Dale, M. Allen and D. Main. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Synergistic Hydrolysis of AFEX Treated Corn Stover and Poplar Using Automated 96-Well Microplate Assay" S. Chundawat, V. Balan and B. E. Dale. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Enzymatic Hydrolysis and Fermentation for AFEX-Treated Corn Stover: An Integrated Biorefinery Approach" L. Sousa, V. Balan, S. Chundawat, D. Marshall, B. Dale, and P. Slininger. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Comparative Sugar Recovery Yields for Pretreatment of Corn Stover and Poplar by Leading Technologies Followed by Enzymatic Hydrolysis of the Remaining Solilds" C.

Wyman, B. E. Dale, R. T. Elander, M. Holtzapple, M. Ladisch, Y. Y. Lee, C. Mitchinson, and J. Saddler. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Relating Enzymatic Hydrolysis Yields to Substrate Features for Corn Stover and Poplar Solids Produced by Leading Pretreatment Technologies" R. Kumar, B. Dale, R. Elander, M. Holtzapple, M. Ladisch, Y. Y. Lee, C. Mitchinson, J. Saddler, and C. Wyman. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Cellulosic Ethanol from AFEX Treated Oil Seed Cakes and Hulls for Bio-Diesel Processing" V. Balan, S. Chundawat, L. Sousa, C. Rogers and B. E. Dale. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Development of a Nanoparticle Based Nanosome to Enhance Enzyme Proximity Synergy between Beta Glucosidase and Cellobiohydrolase" D. Srivastava, S. Chundawat, B. Dale and I. Lee. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Strategies to Conduct Efficient Co-Fermentation on Cellulosic Hydrolysates fromm AFEX-Pretreated Feedstocks" M. Lau and B. E. Dale. Oral Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City, Utah. November 4-9, 2007.

"Field to Fuel: Designing Sustainable Biorefineries" R. Jenkins, C. Alles, S. Hennessey, J. Ginn, D. Culver, B. Vrana, R. Sylvester, J. Friend, M. Emptage, S. Kim and B. Dale. Platform Presentation at the Ecological Dimensions of Biofuels Conference and Workshop. Washington, D. C. March 10-12, 2008.

"Fermentability of Corn Stover Hydrolysates Resulting from Different Pretreatments: A Side by Side Comparison using Different Ethanologens" Platform Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

"Effect of Varying AFEX Pretreatment Severity on Corn Stover Cell Wall Ultra Structure and its Related Degradation Reactions" S. P. S. Chundawat, V. Balan, A. D. Jones, R. Vismeth, R. Garlock, P. Askeland, and B. E. Dale. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

"Comparing AFEX Pretreatment Conditions for Corn Stover Versus Poplar" V. Balan, L. Da Costa Sousa, D. Marshall, S. P. S. Chundawat, and B. E. Dale. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Effect of Drying Method on AFEX Pretreatment and Enzymatic Hydrolysis of Year-Old Poplar” R. J. Garlock, V. Balan and B. E. Dale. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Evaluation of Matrix Interference on Quantitation of Lignocellulosic Degradation Products in Biomass Pretreatment Samples Using LC-ESI-MS-MS” L. N. Sharma, B. Du, C. K. Chambliss, S. P. S. Chundawat and B. E. Dale. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“High Solid Loading Enzymatic Hydrolysis and Fermentation of AFEX Treated Corn Stover” L. Da Costa Sousa, V. Balan, S. P. S. Chundawat, B. E. Dale, and P. J. Slininger. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Effect of Corn Stover Fractions and Harvesting Period on Overall Sugar Yields following AFEX Pretreatment and Enzymatic Hydrolysis” R. J. Garlock, S. P. S. Chundawat, V. Balan and B. E. Dale. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Options for Obtaining Value from Proteins During Ethanol Production from Distiller’s Grains” B. Bals, B. E. Dale, V. Balan, B. Brehmer and J. Sanders. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Synergistic Interactions between Commercial Cellulolytic-Hemicellulolytic Enzymes and their Purified Fractions on AFEX Treated Corn Stover for Varying Pretreatment Severities” S. P. S. Chundawat, V. Balan, D. Gao, A.D. Jones, R. Vismeh, B. D. Bals and B. E. Dale. Poster Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Life Cycle Assessment of Polyhydroxyalkanoates (PHA)” S. Kim and B. E. Dale. Platform Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Environmental and Economic Analysis of the Fully Integrated Biorefinery” E. D. Sendich, B. E. Dale and C. A. Rotz. Platform Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“The Great Lakes Bioenergy Research Center: Transformational Science and Sustainability” B. E. Dale, P. Robertson, K. Keegstra, T. Donohue, R. Amasino, R. Landick, J. Ohlrogge, and M. Sussman. Platform Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

“Proposed Standards for Pretreatment Research: Time to Raise the Bar” B. E. Dale. Platform Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

"Application of Leading Pretreatment Technologies to Poplar Wood: Sugar Recovery, Fermentation Performance and Cost Estimates" C. Wyman, B. E. Dale, R. T. Elander, M. T. Holtzapple, M. R. Ladisch, Y. Y. Lee, C. Mitchinson, and J. N. Saddler. Platform Presentation at the 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

"Enzymatic Hydrolysis and Ethanol Production from AFEX Treated Bagasse at High Solids Loading Using Recombinant Ethanologens" C. Krishnan, V. Balan, and B. E. Dale. Platform Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. November 16-21, 2008.

"Effect of Upland vs. Lowland Variety on Sugar Yields Following Ammonia Fiber Expansion (AFEX) Pretreatment and Enzymatic Hydrolysis of Shawnee and Alamo Switchgrass" R. J. Garlock, V. Balan and B. E. Dale. Platform Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. November 16-21, 2008.

"Process Optimization for Maximum Ethanol Production Using Different Ethanologens from AFEX Treated Rice Straw" C. Zhong, C. Krishnan, M. W. Lau, V. Balan, B. E. Dale and Y. J. Yuan. Poster Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. November 16-21, 2008.

"Enzymatic Hydrolysis of AFEX Treated Corn Stover by Cellulolytic and Hemicellulolytic Synergistic Enzyme Cocktails" S. Chundawat, D. Gao, K. Chandraraj, J. Poland, J. Stege, M. Lipton, V. Balan and B. E. Dale. Poster Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. November 16-21, 2008.

"Extraction of Proteins from Corn Dry Mill Co Product by Bio-Based Solvents" S. Datta, Y. J. Lin, M. C. Negri, R. Datta, B. Bals, B. E. Dale and S. W. Snyder. Platform Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. November 16-21, 2008.

"Separation of Chemicals Produced by Acidogenic Fermentation" S. Datta, Y. J. Lin, M. C. Negri, R. Datta, B. Bals, B. E. Dale and S. W. Snyder. Platform Presentation at the Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. November 16-21, 2008.

Invited Lectures

Dale, B. E. 1982. Invited Seminar on Advances in Cellulose Conversion. Laboratory of Renewable Resources, Purdue University, West Lafayette, Indiana, May 17.

Dale, B. E. 1983. "Alfalfa: A Candidate for Crop Conversion." Invited lecture, Colorado State University Chapter of Sigma Xi, September 16.

Invited Lecturer, Intensive Course (in Spanish) "Advances in Biotechnology," Sponsored by the Mexican Society for Biotechnology and Bioengineering. Mexico City, March 1985.

Dale, B. E. 1986. "Biochemical Reactor Engineering: Putting Some Meat on the Models." Invited Seminar presentation to the Department of Chemical Engineering, University of Colorado, Boulder, Colorado, March 13.

Dale, B. E. 1987. "NMR Applications to Design of Dense Cell Culture Apparatus." Invited Seminar to the Department of Chemical Engineering, University of California at San Diego, California, February 4.

Dale, B. E., L. R. Alvarez-Martinez, R. P. Tengerdy, E. Nebot and H. M'Nasira. 1987. "Design of Solid Substrate Fermenters." Invited presentation (in Spanish) at the Latin American Seminar: Biotechnology in Biomass Production and Waste Management." Antigua, Guatemala, February 18-20.

Dale, B. E. 1987. "Desarrollo Integrado de Processos para Convertir Las Materias Lignocelulosicas." Presented (in Spanish) at the Second National Meeting of the Sociedad Mexicana de Biotecnologia y Bioingenieria, Durango, Mexico, June 23-26. Invited Keynote Speaker.

Dale, B. E. 1987. "Thermodynamic Correlations to Predict Protein Stability." Invited presentation to Pfizer Chemical Corp., Groton, CT, November 20.

Dale, B. E. 1987. "Development of a Thermodynamic Correlation to Predict Protein Stability."Invited presentation to the National Bureau of Standards, Gaithersburg, Maryland, November 23.

Dale, B. E. 1988. Can the Protein Molecule be Treated as a Phase?" Invited presentation to the Department of Chemical Engineering, University of Arizona, Tucson, Arizona, February 24.

Dale, B. E. 1988. "Can the Protein Moleule be Treated as a Phase?" Invited presentation to the Department of Chemical Engineering, University of California, Los Angeles, California, February 26.

Dale, B. E. 1988. "How Engineers Participate in the Commercialization of Biotechnology." Invited presentation at the Biotech Symposium sponsored by Texas A&I University, Kingsville, Texas, November 11.

Invited Lecturer in Short Course "Progress in Recombinant DNA Technology" at Lindenwood College, St. Charles, Missouri, June 27, 1989.

Dale, B. E. 1989. "Predicting the Heat Capacity Change of Protein Unfolding by Group Contribution Methods." Invited presentation to the Department of Chemical Engineering, Washington State University, Pullman, Washington, December 8.

Dale, B. E. 1989. "Understanding Cellular Reaction Networks Using NMR Spectroscopy: Pitfalls and Possibilities." Invited presentation to the Department of Chemical Engineering, Auburn University, April 25.

Dale, B. E. 1989. "Development and Use of a Thermodynamic Method for Predicting Protein Stability." Invited paper at the American Society for Microbiology Conference on Biotechnology, Orlando, Florida, June 22-25.

Dale, B. E. 1989. "A Phase Equilibrium Approach to Predicting the Thermodynamic Parameters of Protein Stability." Invited seminar to the Department of Pharmaceutical Chemistry, University of California at San Francisco, Nov. 9.

Dale, B. E. 1990. "Can Protein Unfolding be Treated as a Phase Transition?" Invited seminar to the Department of Chemical Engineering, Rice University, Houston, Texas, September 20.

Dale, B. E. 1990. "Chemical Engineering for Toxicologists." Invited seminar to the Environmental Toxicology and Pharmacology Group, Texas A&M University, October 15.

Dale, B. E. 1990. "Thermodynamic Approaches to Predict Protein Stability." Invited Seminar presented to Abbott Laboratories, North Chicago, IL, November 12.

Williams, G. W. and B. E. Dale. 1991. "Prospects for High Value Crop and Livestock Products in the Nineties: Advances in Production and Processing Technology." Invited presentation at the World Bank Symposium or Agricultural Issues in the Nineties, Washington, D.C., January 9-11, published in Proceedings of the Eleventh Agriculture Sector Symposium, L. Garbus, A. Pritchard and O. Knudsen, eds., pgs. 228-237.

Dale, B. E. 1991. "Thermodynamic Approaches to Predict Protein Stability." Seminar presented to the Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Maine, February 25.

Dale, B. E. 1991. "Integrating Engineering and Life Sciences." Invited Lecture at the Inauguration of the Affiliation between Texas Women's University with the Texas Engineering Experiment Station, Denton, Texas, April 10.

Dale, B. E. and Y. Wang. 1991. "Thermodynamics of High Temperature Enzymes: A New Predictive Model."Invited paper at the Symposium on Biocatalysis Near or Above 100EC, National Meeting of the American Chemical Society, Atlanta, GA, April 15-19.

Invited Lecturer in "International Short Course on Engineering of Biological Reactions and Processes" at Central American Research Institute for Industry, Guatemala City, Guatemala, May 13-25, 1991.

Dale, B. E. 1991. "Cellulose Pretreatments: Research Directions for the Nineties." Invited panel review paper presented at the Symposium on New Developments in Biological Fuel Production, National Meeting of the American Chemical Society, New York, NY, August 26-30.

Dale, B. E. 1992. "Sustainable Production of Food/Feed from Plants," Invited presentation to the Food Science and Technology Seminar, Texas A&M University, October 14.

Dale, B. E. 1992. "Thermodynamic Approaches to Predict Protein Stability." Invited seminar presentation to the Department of Chemical Engineering, University of Texas at Austin, January 27.

Dale, B. E. 1992. "Bioremediation of Petroleum-Contaminated Soils." Invited Lecture toAnnual Meeting of the Texas Water Pollution Control Association, Houston, Texas, January 30.

Invited Lecturer in International Short Course on "Control and Optimization of Fermentations", sponsored by the National Polytechnic Institute, Mexico City, Mexico, Nov. 13, 1992.

Invited Address to the Annual Meeting of the Texas Cottonseed Crushers Association, Corpus Christi, Texas, June 15, 1992.

Dale, B. E., 1993. "Upgrading Plant Materials by Ammonia Processing," Invited Address to the 42nd Oilseed Processing Clinic, March 8-9, New Orleans, Louisiana.

Dale, B. E., 1993. "A Phase Equilibrium Model for Protein Stability," Invited Lecture at the Center for Macromolecular Design, Texas A&M University, April 14.

Dale, B. E., 1993. "Diffusion and Reaction Phenomena in Biological Systems" and "Predicting the Stability of Proteins". Two invited lectures to the Fourth Advanced Course on Biotechnology Processes: Scaling Up the Production of Recombinant Proteins", at the Institute of Biotechnology of the National Autonomous University of Mexico. Oct. 11-22, (presentations in Spanish).

Dale, B. E., 1993. "Bioremediation of Petroleum Wastes" invited lecture sponsored by the United Nations Industrial Development Organization at the Tampico, Mexico plant of Petroleos Mexicanos, Nov. 29, (presentation in Spanish).

Dale, B. E. 1994. "Understanding Diffusion and Reaction Phenomena in Biological Systems." Invited Lecture to the Cardiovascular Forum, Texas A&M University, February 16.

Dale, B. E. 1994. "AFEX Pretreatment and Conversion of Corn Stover/Fiber to Fermentable Sugars" Invited Lecture to the Corn Utilization Conference V, St. Louis, Missouri, June 8-10.

Dale, B. E. 1994. "Environmental Remediation and Restoration of Contaminated Sites", Invited Keynote Lecture to the Tenth National Student Members Meeting of the Mexican Institute of Chemical Engineers, Morelia, Michoacan, Mexico (in Spanish), Sept. 6-11.

Dale, B. E. 1994. "Biomass Refining", Invited Lecture to the Michigan Biotechnology Institute, East Lansing, Michigan, Nov. 22.

Dale, B. E. 1995. "A Phase Equilibrium Approach to Predict Protein Stability", Invited Lecture to the Department of Chemical Engineering, Michigan State University, East Lansing, Michigan, Feb. 3.

Dale, B. E. 1995. "Reaction Engineering and Genetic Engineering of Cryoimmobilized Organophosphorus Hydrolase (or: The Return on Dr.J. O. L. Wendt's Investment"), Invited Lecture to the Department of Chemical Engineering, University of Arizona, Tucson, Arizona, March 28.

Dale, B. E. 1995. "Bioremediation" Invited Lecture at the First International Meeting on Microbial Ecology, Mexico City, Mexico (in Spanish), May 8-12.

Dale, B.E. 1995. “Predicting Protein Stability.” Invited lecture to the Department of Chemical Engineering, Universidad del Zulia, Maracaibo, Venezuela (in Spanish), November 3.

Dale, B.E. 1995. “The National Research Council’s Biobased Industrial Products Report.” Invited presentation to the Annual Meeting of the New Uses Council, Beltsville, Maryland, November 3.

Dale, B.E. 1996. “Integrating Genetic Engineering and Reaction Engineering for Detoxification of Organophosphorus Compounds.” Invited lecture at the Engineering Foundation Conference on Bioremediation of Surface and Subsurface Contamination. Palm Coast, Florida, January 21-26.

Dale, B.E. 1996. "Can the Protein Molecule be Treated as a Phase?" Invited lecture to the Department of Chemical Engineering, Brigham Young University, Provo, Utah, February 29.

Dale, B.E. and L.H. Lynd. 1996. "Biomass Research at Dartmouth and MSU." Invited lecture to the Energy Systems Program at Princeton University, Princeton, New Jersey, August 7.

Dale, B.E. 1996. "Chemical Engineers and Environmental Remediation: Can we Clean up What we Messed Up?" Invited lecture to the Institute for Environmental Toxicology, Michigan State University, East Lansing, Michigan, October 17.

Dale, B.E. 1996. "Can the Protein Molecule be Treated as a Phase?" Invited lecture to the Department of Chemical Engineering, Ohio State University, Columbus, Ohio, October 31.

Dale, B.E. 1997. "AFEX Pretreatment, Hydrolysis and Fermentation of Corn Fiber by Recombinant Microbes." Invited lecture at the DuPont Corporation, Wilmington, Delaware, March 24.

Dale, B.E. 1997. "AFEX Pretreatment, Hydrolysis and Fermentation of Corn Fiber by Recombinant Microbes." Invited lecture to the Department of Microbiology, Michigan State University, East Lansing, Michigan, March 27.

Dale, B.E. 1997. "Enzymatic Detoxification of Organophosphorus Compounds: Integrating Genetic Engineering and Reaction Engineering." Invited lecture to the Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Michigan, April 18.

Dale, B.E. 1998. "Integrating Genetic Engineering and Reaction Engineering for Detoxification of Nerve Agents." Invited lecture to the Department of Chemical Engineering, University of Akron, Akron, Ohio, April 9.

Dale, B.E.. 1998. "Research and Commercialization Priorities for Biobased Industrial Products". Invited Presentation at the Retreat of the Biobased Products Coordination Council of the U.S. Department of Agriculture Patuxent, Maryland, October 13.

Dale, B.E.. 1999. Invited speaker/participant. "The New Petroleum: Energy and National Security". The Woodrow Wilson Center, Washington, D.C. March 17.

Dale, B.E. 1999. "Greening the Chemical Industry: Research Priorities for Biobased Products", invited lecture to the Dow Chemical Company, Midland, Michigan. February 25.

Dale, B.E. 1999. "Cornucopia or Scarcity? Can we have Biomass for Fuel and Eat it too…??" Invited lecture to the course "Sustainable Resource Supply: The case of plant Biomass" at Dartmouth College, Hanover, New Hampshire. April 22.

Lynd, L., C. Wyman and B.E. Dale. 1999. "Advanced Technologies Supporting a Cellulosic Ethanol-Based Transportation Sector" presented at the Symposium on Energy Technologies – Recent Advances and Future Prospects, The Johns Hopkins University, Washington, D.C. April 28.

Dale, B.E. 1999. "The National Sustainable Fuels and Chemicals Act of 1999" invited testimony before the United States Senate Committee on Agriculture, Nutrition & Forestry. Washington, D.C. May 27.

Dale, B.E. 1999. "'Greening' the Chemical Industry. Research Priorities for Biobased Products,", invited seminar to the Department of Chemical Engineering, Michigan State University, Oct. 21.

Dale, B.E. 1999. "The FIBEX Processing System: Converting Crop residues and Byproducts to Quality Animal Feeds" Invited Keynote Speaker at Information Day 99, sponsored by the Prairie Feed Resource Centre', Saskatoon, Saskatchewan, Canada, Oct. 28.

Dale, B.E. 1999. "Biomass Research and Development Act of 1999." Invited testimony before the U.S. House of Representatives Committee on Science. Washington, D.C. Oct. 28.

Dale, B.E 2000. "Biobased Industrial Products: The Coming of a New Industrial Age?" invited speaker at the 10th Annual Conference of Certified Hazardous Materials Managers of Michigan. Livonia, Michigan, February 10.

Dale, B.E. 2000. "Renewable Resources and Ecological Engineering: New Opportunities for a New Century" invited speaker at the 2nd National Congress of the Mexican Institute of Chemical Engineers Student Conference. Morelia, Michoacan, Mexico. February 16. (given in Spanish).

Dale, B.E. 2000. "Greening the Chemical Industry: Some Priorities for Biobased Products", invited presentation to Dow Chemical Company, Freeport, Texas . April 18.

Dale, B.E. 2000. "National Research Council Report on Biobased Products", invited luncheon speaker at a special symposium sponsored by the Department of Energy "National Biobased Products and Bioenergy Initiative: The Role and Capacities of the State Universities and Land-Grant Colleges", June 15-16 at Iowa State University, Ames, Iowa.

Dale, B.E. 2000. "Cornucopia or Scarcity: Can We Have Biomass for Fuel and Eat It Too?" invited presentation at the Environmental and Energy Study Institute. Washington, D. C. June 19.

Dale, B.E. 2000. "Biobased Industrial Products" invited presentation to the USDA-DOE Interagency Council on Biobased Products and Bioenergy, Beltsville, Maryland. June 20.

Dale, B.E. 2000. "Renewable Resources and Ecological Engineering: New Opportunities for a New Century" Invited Keynote Speaker at the International Symposium on Biotechnology sponsored by the National Polytechnic Institute, Mexico City, Mexico. Sept. 25-29. (given in Spanish)

Dale, B.E. 2000. "Cornucopia or Scarcity: Can We Have Biomass for Fuel and Eat it Too?" invited seminar to DuPont, Inc., Wilmington, Delaware. Nov. 27.

Dale, B.E. 2000. "Biobased Industrial Products: The Coming of a New Industrial Age?" Invited Plenary Lecture at the 9th Annual Meeting of the Bio-Environmental Polymer Society, Honolulu, Hawaii. Dec. 15.

Dale, B. E. 2001. ""Greening" the Chemical Industry: Research Priorities for Biobased Products" Invited Keynote Speaker at the Inaugural Meeting of the Division of Industrial Bio-Based Technology at the 222nd National Meeting of the American Chemical Society. Chicago, Illinois. Aug. 28.

Dale, B. E. 2001. "Toward a Biobased Economy: Challenges and Opportunities for the New Century". Invited Speaker at the 3rd International Value-Enhanced Grains Conference and Trade Show sponsored by the U. S. Grains Council. Portland, Oregon. July 24.

Dale, B. E. 2001. "Cornucopia or Scarcity: Can We Have Biomass for Fuel and Eat It Too?" Invited seminar to the Department of Chemical Engineering, Iowa State University. Ames, Iowa. March 8.

Dale, B. E. 2001. "Economic Opportunities for Agriculture and Forestry from Biomass Conversion" Invited testimony before the Senate Committee on Agriculture, Nutrition and Forestry of the United States Government. March 27.

"Integrated Biorefining Systems: A Sustainable Future Seen Through a Glass, Darkly" Bruce E. Dale. Invited Presentation to the Sustainability Summit, Dow Chemical Company, Midland, MI Dec. 11, 2002

"Net Energy and Global Warming Impact Associated with Producing Biomass for Biobased Industrial Products" Bruce E. Dale (presenter) Invited Presentation to the National Renewable Energy Laboratory, Golden, CO. January 29, 2002

“Biobased Industrial Products and Bioenergy: Some Economic Drivers and Potential Environmental Impacts” Bruce E. Dale, (presenter) Invited Presentation to the U. S. Environmental Protection Agency. Cincinnati, OH May 14, 2002

“Biobased Products Research Capabilities at Michigan State University,” Bruce E. Dale (presenter) Invited Presentation to the National Center for Agricultural Utilization Research, Peoria, IL. March 6, 2002.

“Net Energy and Global Warming Impact Associated with Producing Biomass for Biobased Industrial Products” Bruce E. Dale (Presenter) Invited Presentation to DuPont Central Research and Development, Wilmington, DE. March 21, 2002

“Cornucopia or Scarcity: Can We Have Biomass for Fuel and Eat it Too?” Bruce E. Dale (presenter) Invited Presentation to the Conference of Scholars, sponsored by the Sigma Xi Research Society, Arkansas State University April 16, 2002

“Integrated Biorefining Systems: A Sustainable System Seen Through a Glass, Darkly” Bruce E. Dale. Invited Plenary Lecture. Paper 28b at the Annual Meeting of the American Institute of Chemical Engineers, Indianapolis, IN Nov. 6, 2002.

“Biobased Products, Biorefineries and the Vitality of American Agriculture” Bruce E. Dale (presenter) Invited Presentation to the International Conference on Crop Harvesting and Processing. Louisville, KY February 9, 2003

“Cellulose Pretreatments” Bruce E. Dale (presenter). Invited Presentation to the Genencor Biomass Board. Beloit, WI. March 13, 2003

“Net Energy of Ethanol from Corn: A Comparative Analysis” Bruce E. Dale (presenter) and Seungdo Kim. Invited Presentation to the Rally for the Renewable Fuels Standard-National Corn Growers Association. Washington, D. C. March 18, 2003.

“Why Starch and Cellulose Conversion Complement Each Other and Benefit Farmers” Bruce E. Dale. Invited Presentation to the Board of the National Corn Growers Association. East Lansing, MI June 10, 2003

“Integrated Biorefining Systems for Biobased Products and Bioenergy” Bruce E. Dale (presenter) Invited Presentation to the Association for the Advancement of Industrial Crops. Portland, OR October 13, 2003

“Perspectives on Biomass Supply and Related Issues” Bruce E. Dale (presenter). Invited Presentation to Cargill, Inc. Minneapolis, Minnesota. January 24, 2004.

“Integrated Biorefining Systems for Biobased Products and Bioenergy” Bruce E. Dale (presenter) Invited Presentation to the Department of Chemical Engineering, Michigan Technological University. Houghton, Michigan. February 20, 2004.

"All Biomass is Local: Life Cycle Analysis for an Integrated Biobased Economy" Bruce E. Dale (presenter). Invited Plenary Presentation at the 25th Annual Meeting of the Council for Chemical Research. Tampa Bay, Florida. April 17-20, 2004.

"Some Features of a Large Scale, "Mature" Bioprocessing Industry" Bruce E. Dale (presenter) Invited Plenary Presentation at the First World Congress on Industrial Biotechnology and Bioprocessing. Orlando, Florida. April 22, 2004.

"Life Cycle Analysis: Moving Us Toward Sustainability" Bruce E. Dale (presenter). Invited Presentation to the Engineering Colloquium Series, University of Arizona, Tucson, Arizona. February 22, 2005.

"Overcoming Barriers for Biorefinery Commercialization" Bruce E. Dale (presenter). Invited participant and questioner in a plenary lecture discussion at the World Congress on Industrial Biotechnology and Bioprocessing, Orlando, Florida. April 20-22, 2005.

"Net Energy and Greenhouse Gas Generation of Fuel Ethanol: What is the Truth?" Bruce E. Dale (presenter) and Seungdo Kim. Invited Presentation at the General Motors Technical Center, Warren, Michigan. May 23, 2005.

"Net Energy of Fuel Ethanol" Bruce E. Dale (presenter). Invited participant (one of four) to a nationally televised (on CSPAN) debate/forum on this topic. Washington, D.C. August, 23, 2005.

"Bioenergy and Bioproducts: Some Myths Debunked" Bruce E. Dale (presenter). Invited Presentation to special seminar on Agricultural Biotechnology and Midwest Rural Development sponsored by the Federal Reserve Board of Chicago. September 8, 2005.

"What is the Net Energy of Bioethanol?: A Foolish and Unimportant Question" Bruce E. Dale (presenter) and Seungdo Kim. Invited Presentation to the International Conference on Renewable Resources and Biorefineries. Ghent, Belgium. September 19-21, 2005.

"Recent Research Results of the Biomass CAFI" Charles E. Wyman (presenter) and Bruce E. Dale, et al. Invited Presentation to the 14th European Biomass Conference. Berlin, Germany. October 17-21, 2005.

"Biomass Supply and Biobased Fuels and Chemicals: Some Perspectives" Bruce E. Dale (presenter). Invited Presentation to Ceres Corporation, Thousand Oaks, California. October 19, 2005.

"Beyond Net Energy: Non Renewable Energy Use and Some Environmental Impacts of Corn and Cellulosic Ethanol" Bruce E. Dale (presenter). Invited Presentation to a Forum on the Sustainability of Energy Crops. Iowa State University, Ames, Iowa. November 16, 2005.

"Biomass Fuels and the Bioeconomy: Good Policy Needs Good Information" Bruce E. Dale (presenter),. Invited Presentation to the Forum on Curbing Energy Costs in a Cold Weather, Commuter State. Institute for Public Policy and Social Research. Lansing, Michigan January 25, 2006.

"Biomass and Bioethanol 101" Bruce E. Dale (presenter). Invited Presentation to the Joint Genomics and Metabolic Engineering Workshop, sponsored by the Department of Energy. Bethesda, Maryland. February 12-15, 2006.

"Future Fuels" Bruce E. Dale (presenter). Invited Presentation to the Bureau of Transportation Planning Open House on "Navigating the Future". Lansing, Michigan. March 7, 2006.

"The Case for Cellulosic Ethanol" Bruce E. Dale (presenter). Invited Presentation at the BP Ethanol Forum. New York, New York. March 10, 2006.

"Vision of the Future: Connecting Agriculture and Energy" Bruce E. Dale (presenter) Invited Presentation to the Harvesting Agri-Energy Conference. Saginaw, Michigan. March 15, 2006.

"Biomass Supply and Biofuels: Some Perspectives" Bruce E. Dale (presenter). Invited Presentation to the Larson and Allmaras Lecture Series at the University of Minnesota. April 19, 2006.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation to the Alternative Fuels Symposium sponsored by Diversa Corporation, San Diego, California, May 10, 2006.

"Are Biofuels Truly Sustainable? Some Food, Soil Health and Greenhouse Gas Issues" Bruce E. Dale (presenter). Invited Presentation to the Energy Modeling Forum Workshop on Critical Issues in Climate Change sponsored by the U. S. Department of Energy, Snowmass, Colorado, August 2-3, 2006.

"CAR(s) and the Bioeconomy: Some Emerging Realities" Bruce E. Dale (presenter) and David Hollister. Invited Presentation to the Management Briefing Seminar—Advanced Powertrain Forum sponsored by the Center for Automotive Research (CAR). Traverse City, Michigan, August 11, 2006.

"Vision of the Future: the Bioeconomy and the Farm Economy" Bruce E. Dale (presenter). Invited Presentation to the National Farm Organization, Owosso, Michigan. August 24, 2006.

"Biomass as an Energy Source or Raw Material" Bruce E. Dale (presenter). Invited Presentation to the Michigan Bio-Economy Summit. Lansing, Michigan, September 20, 2006.

"Biomass Refining Global Impact- The Biobased Economy of the 21st Century" Bruce E. Dale, (presenter). Invited Plenary Lecture at the Biorefinica International Symposium, Osnabruck, Germany, October 11-12, 2006.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited

Presentation at the Conference on Tomorrow's Energy….Today sponsored by NextEnergy, Detroit, Michigan, October 23, 2006.

"Bioethanol: Thinking Clearly about Energy and Sustainability Issues" Bruce E. Dale (presenter). Invited Presentation at the Whitney and Anna Harris Conservation Forum. St. Louis, Missouri, October 24, 2006.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation at the MSU-DOE Plant Research Laboratory Symposium on Biofuels from Plants: Opportunities and Challenges. East Lansing, Michigan October 27, 2006.

"Fuel Ethanol: Some Myths and Realities" Bruce E. Dale (presenter). Invited Presentation at the Net Impact Conference on Navigating Global Change. Northwestern University, Evanston, Illinois October 28, 2006.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation at the Michigan Agricultural Credit Conference. East Lansing, Michigan, November 2, 2006.

"Ethanol: Boon or Boondoggle?" Bruce E. Dale (presenter). Invited Presentation at the American Enterprise Institute for Public Policy Research. Washington, D. C. November 8, 2006.

"Biofuels: Thinking Clearly about the Issues" Bruce E. Dale (presenter). Invited Presentation at the Annual Meeting of the Michigan Farm Bureau, Grand Rapids, Michigan November 29, 2006.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation at the Michiana Crops Conference. Shipshewana, Indiana, December 1, 2006.

"Biofuels: Thinking Clearly about the Issues" Bruce E. Dale (presenter). Invited Presentation at General Motors, Detroit, Michigan. December 11, 2006.

"Biorefineries: Bio Demand Beyond Fuels, Chemicals and Polymers" Bruce E. Dale (presenter). Invited Presentation to the Michigan Agri-Business Association 74th Annual Winter Conference and Trade Show. Lansing, Michigan. January 8-10, 2007.

"The Biobased Economy of the 21st Century: A Not So Distant View" Bruce E. Dale (presenter). Invited Presentation to Calvin College. Grand Rapids, Michigan. January 16, 2007.

"Energy Balance and Greenhouse Gas Emission Implications for Large Scale Production of Cellulosic Ethanol" Bruce E. Dale (presenter). Invited Presentation to the South Coast Air Quality Management District. Diamond Bar, California. February 15, 2007.

"The Role of Cellulosic Conversion" Bruce E. Dale (presenter). Invited Presentation at the Agricultural Outlook Forum: Agriculture at the Crossroads: Energy, Farm and Rural Policy. Washington, D. C. March 1, 2007.

"Why Ethanol from Cellulosics is Nearer than You Think" Bruce E. Dale (presenter) Invited Presentation to the Michigan Agricultural Extension Agents Conference. East Lansing, Michigan. March 5, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation to the Michigan Chapter of the Soil and Water Conservation Society. East Lansing, Michigan. March 7, 2007.

"Why Cellulosic Ethanol is Closer than You Think" Bruce E. Dale (presenter). Invited Presentation ot the Michigan Agri-Energy Conference. Lansing Michigan. March 14, 2007.

"Biofuels and Biorefineries: Fuel, Food and Environmental Perspectives" Bruce E. Dale (presenter) Invited Presentation to the Detroit Section of the American Institute of Chemical Engineers. Detroit, Michigan. March 21, 2007.

"Why Ethanol from Cellulosics is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation to PLB 301 Course at Michigan State University. March 22, 2007.

"The Michigan State University Energy Cluster" Bruce E. Dale (presenter). Invited Presentation to the Forest Products Society. Grand Rapids, Michigan. May 15, 2007.

"Fuels from Cellulosic Biomass: Energy Security, Environmental Improvement and Rural Economic Development" Bruce E. Dale (presenter). Invited Presentation at the International Conference for Bioeconomy. Tianjin, China. June 26-28, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation to the National Association of County Extension Agents Annual Meeting. Grand Rapids, Michigan. July 15-19, 2007.

"Why Cellulosic Ethanol is Nearer than You Think: Creating the Biofuels Future" Bruce E. Dale (presenter). Invited Presentation as the 2007 Sterling Hendricks Memorial Lecturer. Boston, Massachusetts. August 20, 2007.

"What Next? Creating the Biofuels Future" Bruce E. Dale (presenter). Invited Presentation to the Public Meeting of the Biomass Research and Development Technical Advisory Committee. Detroit, Michigan. September 10, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation to GM-China Working Group on Ethanol Fuel. Beijing, China. September 21, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation to POET Energy, Sioux Falls, South Dakota. November 16, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited

Presentation to the Strategy Forum, Detroit, Michigan. November 19, 2007.

"Why Cellulosic Ethanol is Nearer than You May Think: Creating the Biofuels Future" B. E. Dale. Invited Keynote Address to the International Annual Meeting of the Tri Societies: American Society of Agronomy, Crop Science Society of America and the Soil Science Society of America. New Orleans, Louisiana, Nov. 4-8, 2007.

"Biofuels: Thinking Clearly about our Energy Options" Invited Presentation. Renewable Energy Forum. Lansing, Michigan, January 12, 2008.

"Grassoline in Your Tank: How Biofuels will Help End our Oil Addiction" Invited Presentation. The Church of Jesus Christ of Latter-day Saints. East Lansing, MI. February 1, 2008.

"Biofuels: Thinking Clearly about our Energy Options" Invited Presentation. University of Wisconsin Energy Initiative. Madison, Wisconsin. Feb. 4, 2008.

"Grassoline in Your Tank: Creating the Biofuels Future" Invited Presentation. Midwest Agricultural Energy Summit. Madison, Wisconsin. Feb. 5, 2008.

"Fundamentals and Economics of the Ammonia Fiber Expansion (AFEX) Process" Invited Presentation. Dairy Forage Research Center. Madison, Wisconsin. Feb. 6, 2008.

"Grassoline in Your Tank: Why Biofuels are Nearer than You May Think" Invited Presentation. Commanders Club. Lansing, MI. February 14, 2008.

"Why Cellulosic Ethanol is Nearer than You Think". Invited Presentation. Capital Area Chapter of the Michigan Society of Professional Engineers. Lansing, Michigan. February 19, 2008.

"Biofuels, Food, Economic Development and the Environment: Designing the Biofuels Future" Invited Presentation. NSF-China Workshop. Tianjin City, China. Feb. 25-27, 2008.

"Bioenergy Conversion Processes" Invited Presentation. Washington International Renewable Energy Conference. Washington, D. C. March 5, 2008.

"Cellulosic Ethanol: Thinking Clearly About Related Energy, Food and Environmental Issues" Invited Presentation. University of Toronto. Toronto, Canada. March 12, 2008.

"Cellulosic Ethanol: Thinking Clearly About Related Energy, Food and Environmental Issues" Invited Presentation. Wayne State University. Detroit, Michigan. March 27, 2008.

"Grassoline in Your Tank: How Biofuels will Help End our Oil Addiction" Invited Presentation. Engineering Alumni Board. Michigan State University. East Lansing, MI. April 18, 2008.

"Thinking Clearly About Energy" Invited Presentation. Earth Day Celebration. Bad Axe, Michigan. April 25, 2008.

"Grassoline in Your Tank: How Biofuels will Help End our Oil Addiction" Invited Presentation. Earth Day Celebration. Bad Axe, Michigan. April 25, 2008.

"Biofuels, Food, Economic Development and the Environment: Designing the Biofuels Future" Invited Presentation. USAIN Conference. Wooster, Ohio. April 27, 2008.

"The Great Lakes Bioenergy Research Center" Invited Presentation. 30th Symposium on Biotechnology for Fuels and Chemicals. New Orleans, Louisiana. May 4-7, 2008.

"Grassoline in Your Tank: How Biofuels will Help End our Oil Addiction" Invited Presentation. Alternative Fuels and Vehicles Conference. Las Vegas, Nevada. May 13, 2008.

"Grassoline in Your Tank: How Biofuels will Help End our Oil Addiction" Invited Presentation. Foundation for the Defense of Democracies Conference. Freeport, Bahamas. May 22, 2008.

"Life Cycle Analysis of Biofuels and Land Use Change" Invited Presentation. Fifth Annual California Biomass Collaborative. Sacramento, California. May 28, 2008.

"The Great Lakes Bioenergy Research Center" Invited Presentation. Biotechnology Industry Organization. San Diego, California. June 18, 2008.

"Beyond Worst Case Scenarios: Biofuels as if Sustainability Mattered" Invited Presentation. Workshop on Measuring and Modeling the Lifecycle GHG Impacts of Transportation Fuels. Berkeley, California July 1-2, 2008.

"Life Cycle Analysis of Biofuels and Land Use Change: A Path Forward?" Invited Presentation. Workshop on Measuring and Modeling the Lifecycle GHG Impacts of Transportation Fuels. Berkeley, California July 1-2, 2008.

"Life Cycle Analysis of Biofuels and Land Use Change: A Path Forward?" Invited Presentation. California Air Resources Board. Sacramento, California July 3, 2008.

"Grassoline in Your Tank: Myths and Realities about Biofuels" Invited Presentation. MM 2008 Green Symposium. Albuquerque, New Mexico. August 4, 2008.

"Fundamentals and Economics of the Ammonia Fiber Expansion (AFEX) Process of Biofuel Production" Invited Presentation. Sandia National Laboratory. Albuquerque, New Mexico. August 5, 2008.

"Land Use Change and Life Cycle Analysis: Biofuels as if Sustainability Mattered" Invited Presentation. General Motors Research and Development Corporation. Warren, Michigan. August 14, 2008.

"Economic, Environmental and Land Use Benefits of Animal Feed Coproduction with

Cellulosic Biofuels" Invited Presentation. Symposium on Developing Biobased Chemicals, Fuels and Materials. Lansing, Michigan. August 25, 2008.

"Thinking Clearly about Biofuels" Invited Presentation. GM Biofuels Summit. Detroit, Michigan. August 29, 2008.

"Land Use Change and Life Cycle Analysis: Designing Biofuels for Sustainability" Invited Presentation. General Motors Corporation. August 29, 2008.

"Cellulosic Ethanol: Thinking Clearly About Related Energy, Food and Environmental Issues" Invited Presentation. Pennsylvania State University. State College, Pennsylvania. Sept. 15, 2008.

"Fundamentals and Economics of the Ammonia Fiber Expansion (AFEX) Process for Biofuel Production" Invited Presentation. Pennsylvania State University. State College, Pennsylvania. Sept. 16, 2008.

"Fuels from Cellulosic Biomass: Energy Security, Environmental Improvement & Rural Economic Opportunities" Invited Presentation. Kurtz Memorial Lecture. University of Iowa. Iowa City, Iowa. Sept. 18, 2008.

"Sustainable Paths to a Biofuel-Powered Transportation Sector: the Role of Invention and Innovation" Invited Presentation. Science Advisory Board- U. S. Environmental Protection Agency. Washington, D.C. October 27, 2008.

"Cellulosic Biofuels: Myths and Realities. Invited Presentation. Science Center. London, England. Nov. 5, 2008.

"Optimizing Cellulosic Biomass Resource Potential: Lessons from the USA. Invited Presentation. Green Supply Chain Conference '08. York, England. Nov. 6, 2008.

"Fundamentals and Applications of the Ammonia Fiber Expansion (AFEX) Process for Biofuel Production" Invited Presentation. TMO Renewables. Guilford, Surrey, England. Nov. 7, 2008.

"Cellulosic Ethanol: Thinking Clearly About Related Energy, Food and Environmental Issues" Invited Presentation. University of Michigan. Ann Arbor, Michigan. Nov. 11, 2008.

"Grassoline in Your Tank: Why Cellulosic Ethanol is Nearer than You Think" Invited Presentation. Sustainable Business Conference. Kalamazoo, Michigan. Nov. 13, 2008.

"All Biomass is Local: Thinking Creatively about Biofuels (or: Biofuels as if Sustainability Mattered). Invited Centennial Plenary Lecture. Annual Meeting of the American Institute of Chemical Engineers. Philadelphia, Pennsylvania. Nov. 17, 2008.

"Fundamentals and Applications of the Ammonia Fiber Expansion (AFEX) Process for Biofuel

Production" Invited Presentation. Dartmouth College. Hanover, New Hampshire. Nov. 24, 2008.

"Grassoline in Your Tank: Why Cellulosic Biofuels are Nearer than You May Think" Invited Presentation. Conference: The Latest on Alternative Energy in Michigan. Lansing Community College. Lansing, Michigan. Dec. 2, 2008.

INVITED WORKSHOPS/PRESENTATIONS TO STUDENT & COMMUNITY GROUPS

Dale, B. E. and H. A. Schroeder. 1987. "Mechanisms of Plant Cell Wall Resistance to Polysaccharide Degrading Enzymes: A Study Using Nuclear Magnetic Resonance Analysis." Biochemical Conversion Program Annual Review Meeting, Solar Energy Research Institute, Golden, Colorado, October 13-15.

Dale, B. E. 1991. "Food and Biochemical Engineering." Seminar presentation to AGEN 489 Sophomore Seminar, March 1.

Dale, B. E., 1992. "Sustainable Production of Food/Fuel from Plants," presentation to the Food Science and Technology Seminar Series, Texas A & M University, October 14.

"Potential for Alternative Fuels from Agriculture in Michigan" Presentation to the Michigan Farm Bureau, Saginaw, MI April 8, 2002.

"Ethanol Energy Study: Non-Food Uses of Corn" Presentation to the Michigan Corn Growers Association. Caro, MI August 2, 2002.

"Research and Development Recommendations" by Lee R. Lynd and Bruce E. Dale. Invited presentation to a Working Group convened by the Governor's Ethanol Coalition meeting on "Ethanol from Biomass: America's 21st Century Fuel" Washington, D. C. January 27, 2005.

"The Ethanol Biorefinery" a Workshop convened by the USDA ARS and BIO to make research and policy recommendations. Orlando, Florida. April 22, 2005.

"Environmental Impacts of the Biobased Economy" Bruce E. Dale (presenter). Invited presentation and report to the Organization for Economic Cooperation and Development Workshop on "Managing the Transition to a Biobased Economy". Ghent, Belgium. December 1-2, 2005.

"Biomass to Biofuels Workshop" Invited participant to this Dept. of Energy sponsored workshop to set research priorities for the next 10 years to significantly expand the biofuels industry. Washington, D. C. December 7-9, 2005.

"Why Ethanol from Cellulosics is Nearer than You Think" Invited Presentation to the Lunch and Learn Club of the University Club. Lansing, Michigan. January 9, 2007.

"Biofuels: Thinking Clearly about the Issues" Invited Presentation to the East Lansing Rotary Club. March 5, 2007.

"Fuel Ethanol: Thinking Clearly about the Issues" Invited Presentation to the East Lansing Kiwanis. March 12, 2007.

"Biofuels: Thinking Clearly about the Issues" Invited Presentation to a community meeting at Montcalm Community College. March 12, 2007.

"Biofuels: Thinking Clearly About the Issues" Invited Presentation to the Central Michigan Group of the Sierra Club. East Lansing, Michigan. March 19, 2007

"Cellulosic Ethanol" Invited Presentation to the Michigan Renewable Fuels Commission. Lansing, Michigan. March 28, 2007.

"Biofuels and Biorefineries: Some Fuel, Food and Environmental Perspectives" Invited Keynote Address to the 17th Annual Student Symposium Day at Michigan State University. East Lansing, Michigan. April 9, 2007

"Why Biofuels?" Invited Presentation to *Experience MSU* (a program held annually to introduce leading MSU activities to wealthy/influential alumni) East Lansing, Michigan, April 20, 2007

"Cellulosic Ethanol: Finding a Smart Plan for Michigan" Invited Presentation to the Michigan Economic Development Corporation's Cellulosic Ethanol Working Group. East Lansing, Michigan. April 20, 2007

"Biofuels: Thinking Clearly About Our Energy Options" Invited Presentation to the Institute of Religion. East Lansing, Michigan. April 27, 2007.

"How We Can End our Petroleum Addiction" Invited Presentation to Mr. Robert Ley's 4th Grade Class at Murphy Elementary School. Haslett, Michigan. May 10, 2007.

"Why Cellulosic Ethanol is Nearer than You Think" Bruce E. Dale (presenter). Invited Presentation at the Hong Kong University of Science and Technology. Hong Kong, China. June 27, 2007.

"Thinking Clearly about Energy" Bruce E. Dale (presenter). Invited Presentation at Hong Kong University. Hong Kong, China. June 27, 2007.

"Why Cellulosic Ethanol" Bruce E. Dale (presenter). Invited Presentation to the College of Chemical Engineering, Tianjin University, Tianjin City, China. June 29, 2007.

“Why Cellulosic Ethanol is Nearer than You Think” Bruce E. Dale (presenter). Invited Presentation to the Japan Biotechnology Association. Tokyo, Japan. July 3, 2007.

“Fuels from Cellulosic Biomass: Energy Security, Environmental Improvement and Rural Economic Development” Bruce E. Dale (presenter). Invited Presentation at the International Conference for Bioeconomy. Tianjin, China. June 26-28, 2007.

“Why Cellulosic Ethanol is Nearer than You Think” Invited Presentation to Community Town Hall meeting in Harbor Beach, Michigan. September 7, 2007.

“Growing Michigan’s Bioeconomy” Invited Presentation to the Regional Economic Development (RED) Team meeting. Lansing, Michigan. September 6, 2007.

“Thinking Clearly About Our Energy Options: Why Cellulosic Ethanol is Nearer than You Think” Invited Presentation to the Science at the Edge Seminar Series, Michigan State University, East Lansing, Michigan. October 5, 2007.

“Why Cellulosic Ethanol is Nearer than You Think” Invited Presentation to the American Association of Cereal Chemists, San Antonio, Texas. October 9, 2007.

“Preparing for the Expanding Bioeconomy” Invited Panel Presentation to the Michigan State University Extension Conference. East Lansing, Michigan. October 11, 2007.

“Developments in Michigan’s Bioeconomy” Invited Presentation at the MichBio Expo, Lansing, Michigan. October 16, 2007.

“Cellulosic Ethanol and Rural Development” Invited Presentation to the United States Department of Agriculture Rural Development- State Outreach Council, Michigan Office. October 25, 2007.

“Why Cellulosic Ethanol is Nearer than You Think: Creating the Biofuels Future” Inaugural Seminar to the Great Lakes Bioenergy Research Center. University of Wisconsin, Madison. October 29, 2007.

“Grassoline in Your Tank: How Biofuels will Help End our Oil Addiction” Invited Presentation at the Frontiers Workshop (science update for Michigan high school teachers). East Lansing, Michigan. December 7-8, 2007.

“Why Cellulosic Ethanol is Nearer than You Think: Creating the Biofuels Future” Lecture to the Bioenergy Class at Michigan State University. East Lansing, MI. January 23, 2008.

“Bioprocess Engineering” Invited Lecture to the Chemical Engineering Class CHE 883. Michigan State University. East Lansing, MI. Feb. 19, 2008.

"Thinking Clearly about Energy" Invited Presentation to the Michigan State University Chapter of the Biomedical Engineering Student Society. East Lansing, MI. March 20, 2008.

"Debate on Fuel Ethanol Between Dr. David Pimentel of Cornell University and Dr. Bruce Dale of Michigan State University" sponsored by the Wellesley College Women's Environmental Society. Nov. 18, 2008.

MEDIA INTERVIEWS/BROAD READERSHIP PUBLICATIONS/BRIEFINGS FOR POLITICAL LEADERSHIP/WEBINARS/PODCASTS

Dale, B. E. 1982. Alfalfa for Food and Fuel. Taped interview for nationwide distribution to radio stations by the American Chemical Society.

Dale, B.E.. 1999. Invited speaker/participant. "The New Petroleum: Energy and National Security". The Woodrow Wilson Center, Washington, D.C. March 17.

Dale, B.E. 2000. "New Industrial Products from Agriculture" radio broadcast interview by Successful Farming Radio Magazine. Detroit Lakes, Minnesota. August broadcasts.

Dale, B. E. 2001. "A Conversation about Cellulosic Ethanol" radio broadcast interview by the Saturday Food Chain of Metrofarm.com, Central Valley, California. Dec. 22.

Dale, B. E. 2002. "Does Ethanol Require more Energy to Produce than it Provides?" Policy briefing for Congressional staff sponsored by the Energy and Environmental Studies Institute. Washington, D. C. July 31.

"Fuel Cells and Alternative Fuels". Guest on WKAR Radio for interview on call-in program. February 1, 2002

"Net Energy of Fuel Ethanol" Interview on Michigan Farm Radio Network. June 26, 2002.

"Biofuels" Interview for Agritalk Radio, Des Moines, Iowa February 12, 2007

"Cellulosic Ethanol" Interview for PBS Television February 19, 2007.
Invited to White House to personally brief President Bush on cellulosic ethanol. February 23, 2007.

"Cellulosic Ethanol" Interview for Edmonton (Alberta) Gazette. March 8, 2007

"Cellulosic Ethanol" Interview for Michigan Farm Radio. March 8, 2007.

"Cellulosic Ethanol" Interview for The Scientist Magazine (London). March 9, 2007.

One hour live interview on biofuels for WTCM Radio, Traverse City. March 23, 2007.

Appeared on WILX TV (Channel 10) about cellulosic ethanol. March 26, 2007.

University issued press release based on my AAAS presentation "With Cellulosic Ethanol, There is No Food vs. Fuel Debate" March 27, 2007.

Quoted in Great Lakes IT Report March 28, 2007 "Cellulosic ethanol ends food vs. fuel controversy"

Interviewed by Smithsonian Magazine on ethanol production. April 2, 2007.

Interviewed by Ethanol Producer Magazine on food vs. fuel debate. April 4, 2007.

On air interview by KPCC (largest NPR station in Southern California) about biofuels and cellulosic ethanol. April 5, 2007.

Interviewed by Lansing City Pulse. April 11, 2007.

Testified about biofuels before the United States Senate Committee on Finance. April 11, 2007.

Interviewed by LiveScience (a science news service syndicated by MSNBC and Fox) on pros and cons of ethanol. April 13, 2007.

Interviewed by CNN Money on cellulosic ethanol. April 17, 2007.

Interviewed about ethanol by The Virginian-Pilot Newspaper. May 25, 2007.

Played major part in GM Ethanol and Cellulosic Ethanol Media Event, Lake Odessa, Michigan. May 29, 2007. Covered by many national and local media outlets. Story aired on the following media outlets: WWMT News (Grand Rapids) May 29, 2007. WLNS TV (Lansing) May 29, 2007. WILX TV (Lansing) May 29, 2007. ABC 53 WLAJ (Lansing) May 29, 2007. Fox 47 News WSYM TV (Lansing) May 29, 2007. Channel 56 (PBS) Detroit August 19, 2007.

Interviewed by Detroit Automotive News. June 4, 2007.

Participated in internet press conference on new directions for corn ethanol industry. June 4, 2007.

Briefing on Cellulosic Ethanol/Laboratory Tour for Senators Carl Levin, Debbie Stabenow and Congressman Mike Rogers June and July, 2007

Interviewed by Chris Holman for the Michigan Business Review. July 19, 2007.

Interviewed by the Detroit News on biofuels in Michigan. July 27, 2007.

Interviewed by Greenwire (a Washington D.C. newswire than covers energy issues). August 9, 2007.

Interviewed by Metro Times newspaper (Detroit). August 10, 2007.

Interviewed for story in New York Times. August 18, 2007.

On air interview by Canadian Broadcasting Corporation. August 24, 2007.

Interviewed by the Detroit Auto Scene. August 24, 2007. Front page story featuring my interview was published Sept. 10, 2007.

Interviewed by Alberta Oil Radio on the emerging bioeconomy. August 28, 2007. Interview aired September 10, 2007.

Interviewed by NPR about biofuels. August 31, 2007.

Interviewed about life cycle impacts of biofuels by the Science and Technology Policy Institute. September 3, 2007.

Interviewed by Grand Rapids Business Journal. September 9, 2007.

Interviewed by Huron Daily Tribune. September 10, 2007.

Interviewed by WWJ Newsradio 950 (CBS). September 11, 2007.

Interviewed by St. Louis Post Dispatch. September 16, 2007.

Interviewed by Fox News Network on alternative fuel sources. October 19, 2007.

Interviewed by Nature Climate Change on biofuels. November 2, 2007.

Interviewed by New York Times on petroleum alternatives. November 5, 2007.

Interviewed by Wisconsin Public Radio on bioenergy and biofuels. November 14, 2007.

Op-ed article in The Detroit News Friday November 30, 2007. “Biofuel Provides an Answer—without Hiking Food Prices”

“The Costs of Biofuels: A debate on ethanol” Published by the American Chemical Society in *Chemical and Engineering News.* December 17, 2007. Pgs. 12-15

Beginning in 2008 I stopped recording details of most media interviews and only recorded the most important ones. I did keep track of total numbers of media interviews and other notable public outreach efforts.

"Biofuels, Food, Economic Development and the Environment: Designing the Biofuels Future" Webinar on the Future of Biofuels. March 26, 2008.

"Life Cycle GHG Assessment for Biofuels" Webinar Sponsored by the Midwest Climate Consortium. July 25, 2008.

"Economic and Environmental Sustainability of Biofuels" Invited Testimony to the U. S. Senate Agriculture Committee. Omaha, Nebraska. August 11, 2008.

" Biofuels: Myths and Realities" Invited Speaker to the GM Biofuels Summit. Detroit, Michigan. August 27, 2008

"Good Science Needs Good Policy" op ed piece published in the *Washington Times,* Nov. 12, 2008.

PATENTS

Tsao, G. T., M. R. Ladisch and B. E. Dale. 1981. Nontoxic cellulose solvent and process for forming and utilizing the same. U.S. Patent No. 4,265,675.

Dale, B. E. 1986. Method for increasing the reactivity of cellulose. U.S. Patent No. 4,600,590.

Dale, B. E. 1986. Method for increasing the reactivity of cellulose. Australia Patent No. 555217.

Dale, B. E. 1986. Method for increasing the reactivity of cellulose. Brazil Patent No. 8205849.

Dale, B. E. 1987. Method for increasing the reactivity of cellulose. New Zealand Patent No. 202057.

Dale, B. E. 1987. Method for increasing the reactivity of cellulose. South Africa Patent No. 82/7241.

Dale, B. E. 1988. Method for increasing the reactivity of cellulose. Canadian Patent No. 1,240, 671

Dale, B. E. 1988. Method for increasing the reactivity of cellulose. European Patent No. 0077287.

Dale, B. E. 1991. Process for increasing the reactivity of cellulose - containing materials. U. S. Patent No. 5,037,663.

Dale, B. E. 1992. Method for increasing the reactivity of cellulose, Japanese Patent No. 1,667,521.

Dale, B. E. 1993. Method for increasing the reactivity of cellulose, Mexican Patent No. 164,803.

Dale, B. E. and Justin K. Weaver. 2000. U. S. Patent # 6,106,888 "Process for Treating Cellulosic Materials"

Dale, B. E. and Justin K. Weaver. 2001. U. S. Patent # 6,176,176 "Apparatus for Treating Cellulosic Materials"

Dale, B. E. and Justin K. Weaver. 2003. New Zealand Patent #507,774 "Process and Apparatus for Treating Cellulosic Materials"

Dale, B. E. and Justin K. Weaver. 2004. Russian Patent #2239329 "Process and Apparatus for Treating Cellulosic Materials"

Dale, B. E. and Justin K. Weaver. 2004. Chinese Patent #99807580.9 "Process and Apparatus for Treating Cellulosic Materials"

Sticklen, M. B., Dale, B. E. and Shahina Maqbool. 2006. U. S. Patent #7,049,485. "Transgenic Plants Containing Ligninase and Cellulase Which Degrade Lignin and Cellulose to Fermentable Sugars".

CURRENT RESEARCH GRANTS AND CONTRACTS

PAST RESEARCH PROJECTS (ENTIRE CAREER)

- "AFEX Pretreatment of Corn Stover: Optimization of Hemicellulase Activity" U. S. Dept. of Agriculture through MBI, International $67,873. July 15, 2003- July 14, 2004
- "Vice President for Research, Michigan State University. "System Studies of Biobased Products". $95,000. 7/1/02 to 6/30/04
- Fundamentals of Neutral and High pH Biomass Pretreatments to Reduce Sugar Costs through a Concerted Research Approach" Co-PI (Sponsored by the U. S. Department of Energy) $109,808. 10/01-9/02

- Bruce E. Dale (PI) “AFEX Pretreatment Research” U. S. Department of Agriculture through MBI, International. $67,873 July 15, 2003- July 14, 2004. Supports one graduate student. All funds expended.

- C. Wyman, B. Dale, M. Holtzapple, Y. Lee, M. Ladisch. U. S. Department of Agriculture. “Coordinated Development of Leading Biomass Pretreatment Technologies”. Oct. 1, 2000- Sept. 30, 2003. Total project budget $1,250,000.

- M. Worden, J. Ohlrogge and B. Dale. U. S. Department of Education. “Multidisciplinary Training Program for Biobased Industrial Products” Aug. 15, 2000 – Aug. 14, 2003. $612,000. Approximately $12,000 expended to date to support one graduate assistant.

- Bruce E. Dale “AFEX Treatment of Switchgrass” U. S. Department of Agriculture through MBI, International. $67,000 Oct. 1, 2002—Sept. 31, 2003.

- Lawrence T. Drzal and Bruce E. Dale “Microcrystalline Cellulose Nanowhiskers from Biomass” U. S. Department of Agriculture through MBI, International. $131,383. Oct. 1, 2002—Sept. 31, 2003

- Lawrence T. Drzal, Amar K. Mohanty, Satish Joshi and Bruce E. Dale. “Design and Engineering of Green Composites from Biofibers and Bacterial Bio-Plastics. National Science Foundation. September 1, 2002 – August 31, 2003. $98,5000

- “Capability Study of Midwest Consortium for Biobased Products” Co-PI (Sponsored by the U. S. Department of Energy) $50,000. 7/01-9/01

- B. Dale. Michigan State University. Office of Vice President for Research and Graduate Studies. “Center for New Plant Products and Processes-a New Research Excellence Fund Center” Aug. 1, 2000- July 31, 2003. $600,000

- “Development of a Predictive Method for the Digestibility of Ammonia Treated Plant Biomass”, P.I., (Sponsored by MBI, International) $52,000 1/99-12/00

- “The Dow Brine Disposal Ponds: Restoration of Ecological Brownfield” Co-PI, (Sponsored by Dow Chemical Company) $357, 787. 1/1/00 – 5/31/01.

- “Unlocking Fermentable Sugars in Maize Plants via Genetic and Process Engineering”, Co-PI, (Sponsored by IRGP Program, MSU) $74, 909 5/99 – 9/00.

- “Cellulase Expression in Transgenic Maize” Co-PI, (Sponsored by Crop and Food Bioprocessing Center) $25,000, 7/99-6/00.

- Army Research Office, "An Integrated Approach to Understanding the Factors Controlling the Biodegradation of Military Toxic Wastes," $2,328,000, 7/92-12/95; Principal Investigator/Project Director.

- National Institutes of Health, "Environmental Toxicology Training Grant," $528,000, 7/92-12/95; Co-principal Investigator.

- U. S. Department of Agriculture, "Forage, Biomass and Biogas Integrated Systems for Animal Waste Management," $102,000, 4/94 - 12/95; Co-principal investigator.

- Environmental Protection Agency, "Optimization of Treatment Technologies for Detoxification of PCB-Contaminated Soils," $33,700, 6/94 - 12/95.

- U. S. Department of Agriculture, "Pretreatment, Hydrolysis and Fermentation of Corn Fiber", $40,000, 10/94-12/95; Principal Investigator.

- Colorado State University, "Protein Recovery from Corn Residue", $430, 9/79-6/80

- Colorado Energy Research Institute, "Kinetics of Cellulose Recrystallization", $4,198, 6/80-4/81

- Western Alfalfa Corporation, "Protein and Alcohol Production from Alfalfa", $9,300, 6/80-12/80

- Solar Energy Research Institute, "Protein Recovery from Leafy Crop Residues during Biomass Conversion" $16,565, 1/81-9/81

- National Science Foundation, "Differential Scanning Calorimeter for Food and Energy Research", $37,590, 4/81-9/81

- U. S. Department of Energy, "Methanol Production from Fermentor Off-Gases", $42,672, 7/81-6/82

- U. S. Department of Agriculture, "Alfalfa: A Promising Biomass Energy Resource", $79,200, 9/81-9/83

- Colorado Commission on Higher Education, "Water Efficient Crops for Colorado", $16,954, 4/82-3/83

- Atlantic Richfield Corporation, "Kinetics of Leaf Protein Coagulation", $25,000, 6/82-5/84

- U. S. Department of Agriculture, "A Freeze-Explosion Method for Increasing Cellulose Hydrolysis", $79,082, 8/82-7/84

- National Science Foundation-U. S. Dept. of Agriculture, "International Travel Grant", $3,600, 2/84

- Manville Corporation, "Porous Agitators for Immobilized Cell Bioreactors", $35,073, 4/84-3/85

- Saskatchewan Research Council, "Freeze Explosion Treatment of Salt Tolerant Grasses" $8,900, 4/84-6/85

- National Bureau of Standards, "Diffusion and Reaction Phenomena in Immobilized Cell Bioreactors", $24,500, 9/84-8/85

- National Science Foundation, "NMR Analysis of Cations and the Proliferative Response" $133,638, 4/85-3/87

- Colorado Advanced Technology Institute, "Mammalian Cell Bioreactor Analysis by On-Line NMR", $12,000, 7/85-6/86

- Chemical Process Corporation, "Wiped Film Reactor Characterization", $13,800, 10/85-9/86

- Tennessee Valley Authority, "Enzymatic vs. Acid Hydrolysis of Forages" $9,800, 9/85-8/86

- National Science Foundation, "Solid Substrate Fermentation and Cellulose Hydrolysis", $41,500, 12/86-11/88

- National Science Foundation, "Moisture and Temperature Control in Solid Substrate Fermentation, $95,000, 12/86-11/88

- Solar Energy Research Institute, "NMR Analysis of Mechanisms of Resistance of Cell Wall Materials, $39,000, 6/87-5/88

- Colorado Advanced Technology Institute, "Increasing Oxygen Delivery in Hollow-Fiber Bioreactors" $10,700, 11/87-5/88

- Quaker Oats Corporation, "Kinetics of Enzymatic Reactions in Foods", $17,400, 10/87-1/88

- National Institutes of Health , "Development of a Resource for NMR of Mammalian Cells" $297,000, 8/88-5/91

- National Science Foundation, "Testing a Model for Predicting Protein Stability", $29,000, 6/88-12/88

- Institute for Biosciences and Technology (Texas A&M), "Bioreactors for Insect Cell Culture", $155,000, 1/89-12/91

- Solar Energy Research Institute, "Analysis of the Ammonia Freeze Explosion Process" $49,500, 6/89-5/90

- Advanced Technology Program-State of Texas, "Protein Separations using Porous Silicon" $173,000, 1/91-12/92

- Energy Research Applications Program-State of Texas, "Integrated Conversion of Coastal Bermudagrass", $165,000, 6/91-5/93

- Center for Energy and Mineral Resources-Texas A&M University, "Net Energy Analysis of Fuel Ethanol from Lignocellulose: A Public Policy and Research Guide", $23,700, 9/1/92-8/31/93

- U. S. Dept. of Agriculture, "Crop Processing Partnership", $42,000, 9/91-3/93.

TEACHING EXPERIENCE

Undergraduate

Colorado State University
Engineering Principles (EG 101, 102), taught 7 semesters 1980-1986
Reactor Design (CH 420), taught four semesters, 1980-1983
Chemical Engineering Thermodynamics (CH 310), taught 3 semesters 1985-1988
Senior Seminar (CH 493), 1983
Unit Operations I and II (CH 304 & 305), taught 2 semesters 1987-1988

Texas A&M
Heat Transfer (CHEN 323), taught 2 semesters 1990-1991
Mass Transfer (CHEN 424), taught 1993
Biochemical Engineering (CHEN 471), taught 1993
Heat Transfer (CHEN 323), taught 2 semesters, 1993-1995

Michigan State University
Material and Energy Balances (CHE 201)
Chemical Engineering as a Profession (CHE 301)
Process Dynamics and Control (CHE 432)
Biochemical Engineering (CHE 481)
Green Engineering (CHE 491/691)

Graduate

Colorado State University
Advanced Reactor Design, (CH 505), taught 3 semesters 1981-1983
Graduate Seminar (CH 693), 1981
Fundamentals of Biochemical Engineering (CH 504), taught 3 semesters, 1984-1987

Texas A&M
Fundamentals of Biochemical Engineering (CHEN 651), taught 3 semesters 1988-1990
Biochemical Process Technology (CHEN 652), taught 1992

RESEARCH STUDENTS GRADUATED

Ravindranath S. Joshi, Protein Extraction from Alfalfa, M.S., 1981
Jerald A. Andersen, Alfalfa Refinement for Feed and Fuel, M.S., 1982
Maria Silvia Bertran, Cellulose Crystallinity: Influence on Enzyme Hydrolysis and Estimation by a Proposed Calorimetric Method, M.S., 1983
Steven C. Lindbergh, The Acetone-Butanol Fermentation of Cheese Whey, M.S., 1983
Michael G. Doremus, Agitation and Pressure Effects on the Acetone-Butanol Fermentation, M.S., 1983
Kalif Y. Ahmed, Thermal Coagulation Kinetics of Alfalfa Leaf Proteins, M.S., 1984
Venkataraman Bringi, A Comparative Kinetic Study of Free and Immobilized Yeast Cells, M.S., 1985
Ming Shiang, Production, Action and Denaturation of the Cellulases of Trichoderma reesei Rut-C3) on Different Celluloses, M.S., 1985
Kate M. V. Baptie, Cellulase Recycle by Induced Desorption via pH and Temperature Changes, M.S., 1985
Michael R. Melick, Mathematical Modeling of Ethanol Production by Immobilized Zymomonas mobilis in a Packed Bed Reactor, M.S., 1985
David D. Drury, Design of an Oxygen-Limited Bioreactor for Use in a Nuclear Magnetic Resonance Spectrometer, M.S., 1986, coadvised with R. J. Gillies
Margaret L. Hevezi, A Study of Activated Sludge Bulking: Microorganisms, Growth Kinetics and Modeling, M.S., 1986
Chih-Ming Li, Cellulase Desorption in a Batch Reactor, M.S., 1986
Lucas R. Alvarez-Martinez, Modeling Fungal Growth on Extruded Corn by Solid Substrate Fermentation, Ph.D., 1987
Thomas J. Chresand, Diffusion and Reaction in a Hollow Fiber Mammalian Cell Bioreactor, M.S., 1987, coadvised with R. J. Gillies
Shari L. Hanson, Enhanced Oxygen Transfer to Hybridomas in a Hollow Fiber Bioreactor by Perfluorocarbon Emulsions, M.S., 1988, coadvised with R. J. Gillies
Linda M. Barstow, Temperature and Moisture Content Control of a Solid Substrate Fermentation on Extruded Corn, M.S., 1988
Habib M. M'Nasria, Modeling Sugar Consumption by Fungi Growing on Solid Substrates, Ph.D., 1988
David R. Mitchell, Nuclear Magnetic Resonance Studies of Cell Wall Components and Their Enzymatic Transformation, M.S., 1988
Thomas J. Blute, Cell Density Measurements in Hollow Fiber Bioreactors, M.S., 1988, coadvised with R. J. Gillies
Sarah Waterman Jachim, Renaturation Kinetics of Recombinant Secretory Leucoprotease Inhibitor, M.S., 1988
Natarajan Raghunand, Modeling Glycolysis in Hybridomas, M.S., 1990
Mayra E. Rodriguez, Kinetic and Thermodynamic Characterization of Aflatoxin B, Biotransformation in the Rodent Liver, M.S., 1990
Shannon M. Pass, Protein Separation with Porous Silicon Membranes, M.S., 1991
Jorge D. Blasig, Volatile Fatty Acid Fermentation of AFEX-Treated Newspaper and Bagasse by Rumen Microorganisms, M.S. 1991
Kun-Jiang Hsiao, Modeling NMR Compatible Hollow Fiber Bioreactors, Ph.D., 1992

Luis de la Rosa, Development of an Integrated Process for Refining Coastal Bermuda Grass, M.S., 1992

Su Chin Wu, Kinetic Characterization of Baculovirus-Infected Insect Cell Cultures, Ph.D., May 1993, coadvised with J. C. Liao.

Sultan Reshamwala, The Conversion of Biomass to Ethanol and Microbial Biomass Protein, M.S., May 1994.

Natarajan Raghunand, Regulation of Central Metabolism in Baculovirus-Infected Insect Cell Cultures, Ph.D., December 1994.

Ya Jun Wang, Folding, Purification and Stability of Eclosion Hormone, Ph.D., December, 1995.

Mark Shelley, Thermodynamic Characterization of TNT Biodegradation Pathways, M. S., December 1995.

Lin Wang, Computer Simulation and Economic Analysis of the Ammonia Fiber Explosion Process, M.S., May 1996.

William A. Plaehn, Impact of Dissolved Organic Matter on the Desorption Rate and Mineralization Rates of Napthalene, M.S., June 1997.

Marjorie S. Hong, Chemical and Biological Detoxification of Organophosphorus Compounds, Ph.D., August 1997.

Alexis Ferrer, Integrated Conversion of Forages for Ruminant and Non-Ruminant Feeds, Ph.D., December, 1997.

Justin Weaver, Ammonia Fiber Explosion by Extrusion Processing, M.S., May 1998.

Stephanie Luster-Teasley, M. S. Chemical Engineering received Spring 2000. M. S. Thesis title "The Effect of Ozonated Chrysene Byproducts on Gap Junctional Intercellular Communication in Rat Liver Endothelial Cells"

Lisa E. Gollapalli, M. S. Chemical Engineering received May 2001. "Predicting the Enzymatic Digestibility of Ammonia Treated Rice Straw"

Farzaneh A. Teymouri, "Pretreatment and Enzymatic Hydrolysis of Corn Stover" Ph. D. received May, 2003

Lizbeth Laureano-Perez. "Understanding the Factors Limiting Enzymatic Hydrolysis of Lignocellulose" Ph. D. received August, 2005.

Christopher M. Saffron, "Plant Enhanced Remediation of Napthalene" Ph. D. received December 2005.

Tamika C. Bradshaw, "Enzymatic Hydrolysis of Ammonia Fiber Explosion (AFEX) Pretreated Reed Canarygrass and Switchgrass" M.S. received December 2005.

CURRENT RESEARCH STUDENTS

Tao Wang. Ph. D. Chemical Engineering expected Spring 2008. Thesis title: "Nanowhiskers from Cellulosic Materials"

Elizabeth Newton. Ph. D. Chemical Engineering expected August 2008. Thesis title: "Life Cycle Analysis of Biobased Products"

Shishir Chundawat. Ph. D. Chemical Engineering expected August 2008. Thesis title: "Understanding Interactions of Multiple Enzymes with Cellulosic Biomass"

Bryan D. Bals. Ph. D. Chemical Engineering expected August 2008. Thesis title: "Protein Extraction and Recovery from Cellulosic Biomass"

Ming Weoi Lau. Ph. D. Chemical Engineering expected August 2009. Thesis title: "Simultaneous Saccharification and Fermentation of Sugars from AFEX treated Biomass"

Rebecca Garlock. Ph. D. Chemical Engineering expected August 2010. Thesis title: "Genetic Modification of Plant Material and Resulting Effects on Pretreatment and Enzymatic Hydrolysis"

POSTDOCTORAL STUDENTS/VISITORS

Dr. Bahaa T. Shawky, Visiting Fulbright Fellow (from Institute of Microbial Chemistry, National Research Center, Cairo, Egypt), December 1992-April 1994. Microbial Conversions of Plant Biomass to Useful Products

Dr. Mohammed Moniruzzaman, Postdoctoral Student, August 1994-December 1995. Fermentation of Five Carbon Sugars to Ethanol

Dr. Seungdo Kim, Visiting Research Professor. April 2001-present. Sustainability of Biobased Producsts

Dr. Venkatesh Balan, Postdoctoral Associate. February 2005-present. Biomass conversion.

PROFESSIONAL ACTIVITIES

Cochairman of Symposium on Fuels and Chemicals from Biomass, 182nd National Meeting of the American Chemical Society, New York, NY, August 23-28, 1981.

Chairman of Symposium on Biomass Refining: Developing the Whole Plant Concept, 186th National Meeting of the American Chemical Society, Washington, D.C., August 28-September 2, 1983.

Cochairman of Symposium on Reaction Kinetics in Foods and Food Processing, Summer National Meeting of the American Institute of Chemical Engineers, Denver, Colorado, August 28-31, 1983.

Cochairman of Symposium on Fundamentals of Anaerobic Fermentations. Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California, November 25-30, 1984.

Invited Participant, U.S./Spain Joint Workshop on Biochemical Engineering, Sponsored by National Science Foundation, Valencia, Spain, November 1984.

Chairman of Symposium on Pretreatment and Processing of Lignocellulosic Materials, 190th Annual Meeting of the American Chemical Society, Chicago, Illinois, September 8-13, 1985.

Cochairman of Symposium on Molecular Changes in Proteins in Chemical Engineering. Annual Meeting of the American Institute of Chemical Engineers. Miami Beach, Florida, November 2-7, 1986.

Cochairman of Symposium on Biosensors at the Conference on Frontiers in Bioprocessing. Sponsored by the National Bureau of Standards, Boulder, Colorado, June 28-July 2, 1987.

Cochairman of Symposium on Engineering Fundamentals of Food Processing Systems. 1987 National Meeting of the American Institute of Chemical Engineers, Minneapolis, Minnesota, August 16-19, 1987.

Cochairman of Meeting Program for the Division of Microbial and Biochemical Technology of the American Chemical Society at the Third Chemical Congress of North America, Toronto, Canada, June 5-11, 1988.

Cochairman of the General Papers Session of the Division of Microbial and Biochemical Technology of the American Chemical Society at the Third Chemical Congress of North America, Toronto, Canada, June 5-11, 1988.

Chairman of the Symposium on Membrane Applications in Bioseparations for the Division of Industrial and Engineering Chemistry of the American Chemical Society at the Third Chemical Congress of North America, Toronto, Canada, June 5-11, 1988.

Chairman of the Symposium on Technical and Economic Aspects of New Processes for Adding Value to Agricultural Raw Materials at the National Meeting of the American Institute of Chemical Engineers, Denver, Colorado, August 21-24, 1988

Chairman of the Symposium on Ethanol Production and Use in Fuels at the National Meeting of the American Institute of Chemical Engineers, Denver, Colorado, August 21-24, 1988.

Cochairman of the Symposium on Monitoring and Modelling of Toxic Waste Degradation at the Meeting of the American Chemical Society, April 9-14, 1989.

Cochairman of Symposium on Separation of Bioactive Compounds: Engineering Fundamentals at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, California, Nov. 5-10, 1989.

Invited Participant in the Workshop "Cattle on the Land," Carlsbad, California, Dec. 12-15, 1990.

Chairman of the Working Group on Risk Assessment, National Workshop on Food Safety, Texas A&M University, College Station, Texas, June 25-29, 1991.

Participant in the NASA Workshop on Resource Recovery from Wastes Generated in Lunar/Mars Controlled Ecological Life Support Systems (CELSS), League City, Texas, August 12-14, 1991.

Chairman of the NASA Workshop on Regenerative Life Support Systems, Houston, Texas, November 1, 1991.

Panel Reviewer, USDA Small Business Innovation Research Program, February 19, 1992.

Invited Participant, USDA/DOE Workshop on "Technology for Expanding the Biofuels Industry," Chicago, Illinois, April 21-22, 1992.

Invited Participant in the U.S. Department of Energy Workshop on Energy Engineering Research, Washington, D.C., Oct. 29-31, 1993.

Chairman of Symposium on Industrial Materials from Agricultural Products, 1994 Science Conference of the Agriculture Program, Texas A&M University, January 10, 1994.

Cochairman of the Session "Thermal, Chemical and Biological Processing" for the Sixteenth Symposium on Biotechnology for Fuels and Chemicals, Gatlinburg, Tennessee, May 9-13, 1994.

Chairman of the Conference on Liquid Fuels, Lubricants and Additives from Biomass, sponsored by ASAE, Kansas City, Missouri, June 15-18, 1994.

Cochairman of Session #5: “Emerging Topics in Industrial Biotechnology” for the Eighteenth Symposium on Biotechnology for Fuels and Chemicals, Gatlinburg, Tennessee, May 5-10, 1996.

Member of the Scientific Committee for the Conference on Biofuels and Alternative Fuels, Leece, Italy, August 21-24, 1996.

Member of the Scientific Committee for the International Symposium on Biofuel and Industrial Products, Managua, Nicaragua, February 23-27, 1996.

Cochairman (with Charles J. Arntzen) of National Research Coucil on “Biobased Industrial Products: Research and Commercialization Priorities”. Panel report issued March 2000.

Member National Research Council Committee to "Review the R&D Strategy for Biomass-Derived Ethanol and Biodiesel Transportation Fuels". Panel report issued September, 1999.

Member of Program Review Team to review the Department of Biological Systems Engineering at Virginia Polytechnic Institute and State University, Blacksburg, Virgina, September 6-9, 1998.

1999 Meeting Program Chair for the Food, Pharmaceutical and Bioengineering Division of the American Institute of Chemical Engineers.

1996-2002 Member, Executive Committee of the Food, Pharmaceutical and Bioengineering Division of the American Institute of Chemical Engineers.

Cochaired Session #4 "Biotechnology and Bioproducts: Forum on Recent Government Initiatives" at the 22nd Symposium on Biotechnology for Fuels and Chemicals" Gatlinburg, Tennessee. May 9, 2000.

Member of the Organizing Committee for the Symposium on Biotechnology for Fuels and Chemicals held annually in May in Colorado or Tennessee 1985-2001.

Member of the External Advisory Board of the Plant Sciences Institute at Iowa State University 2001-present

Cochaired Session #316 "Biobased Industrial Products: Where are We and Where are We Going?" at the Annual Meeting of the American Institute of Chemical Engineers, Reno, Nevada. November 5, 2001.

Cochaired Session #27 "Pretreatment of Lignocellulosic Biomass II" at the Annual Meeting of the American Institute of Chemical Engineers, Indianapolis, IN. November 5, 2002.

Cochaired Session on "Biomass Pretreatment and Hydrolysis" at the 25th Symposium on Biotechnology for Fuels and Chemicals, Breckenridge, CO May 7, 2003

Cochaired Session #165 "Reactor Engineering for Biomass Feedstocks" at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, CA. November 21, 2003.

Cochaired Session #33 "Reactor Engineering for Biomass Feedstocks" at the Annual Meeting of the American Institute of Chemical Engineers, Austin, TX. November 11, 2004.

Cochaired Session on "Sustainability Issues" at the World Congress on Industrial Biotechnology and Bioprocessing, Orlando, FL April 21-23, 2004.

Member of the Program Committee for the World Congress on Industrial Biotechnology and

Bioprocessing, Orlando, FL April 21-23, 2004.

Session Chair for "Recent Research Results of the Consortium for Applied Fundamentals and Innovation" at the Biotechnology Industry Organization (BIO) International Convention, Chicago, Illinois, April 12, 2006.

Session Co-Chair for Special Topic "Life Cycle Analysis/Sustainability" at the 28th Symposium on Biotechnology for Fuels and Chemicals, Nashville, Tennessee, May 2, 2006.

Chair of International Roundtable on Sustainable Biofuels (a project of ETH Lausanne, Switzerland). July 2007- present.

REVIEWER FOR

Biotechnology and Bioengineering (2001, 2002, 2003)
Biotechnology Progress (2003)
Biomass and Bioenergy (2003)
ACS Symposium Series
McGraw Hill Book Corp.
Dept. of Chemical Engineering, Univ. of Minnesota, 1990 (Promotion/Tenure Review)
Thayer School of Engineering, Dartmouth College, 2001, 2002, 2003 (Promotion/Tenure Review)
Biological Systems Engineering Department, Virginia Polytechnic Institute and State University, 2001 (Promotion/Tenure Review)
Department of Chemical Engineering and Department of Agricultural and Biological Engineering, Iowa State University, 2003 (Two Promotion/Tenure Review)
Applied Biochemistry and Biotechnology (2001, 2003)
National Science Foundation
U.S. Dept. of Agriculture Industrial Applications Panel Reviewer (2003)
Bioresource Technology (2001)
John Wiley & Sons
North Carolina Biotechnology Center
First International Symposium on Bioprocess Engineering
Journal of Solar Energy Engineering
Ethanol Technology Handbook
Consortium for Plant Biotechnology Research
Mexican Society of Biotechnology and Bioengineering
Bioprocess Engineering
Journal of the American Institute of Chemical Engineers
Intramural Research Grants Program-Michigan State University (2001)
Thayer School of Engineering, Dartmouth College, 2002 (Promotion/Tenure Review)
University of Arizona, 2002, (Promotion/Tenure Review)
Oregon State University, 2002 (Promotion/Tenure Review)

UNIVERSITY/PUBLIC SERVICE

DEPARTMENT

- Presentation on Chemical Engineering to Career Days at Dwight Rich Middle School, May 21, 1999.
- Representative to Institute for Global Engineering Education, 1997 – 2001.
- Chairperson Search Committee, 2001-2002, 2006-2008
- Member of Strategic Planning Committee 2001-
  - Chemical Engineering Department Library Representative 1994
  - Chemical Engineering Graduate Committee 1989-1993
  - Safety Committee, Summer 1991
  - Agricultural Engineering Promotion and Tenure Committee 1993-present
  - Agricultural Engineering Undergraduate Program Committee 1993-present
  - JETS Conference (Agricultural Engr) 1990
  - Agricultural Engineering Graduate Affairs Committee, 1989-1993
  - Representative to University Library Committee, 1979-1986
  - Graduate Student Recruitment Committee, 1982-1984 (included preparation of a full color recruitment brochure)
  - Department Head Search Committee, 1984
  - Ph.D. Administration Committee, 1984-1988
  - Tenure and Reappointment Committee, 1984-1988
  - Career Days Presentation, 1985, 1986
  - Advisor to Omega Chi Epsilon (Chemical Engineering Honor Society) 1985
  - Led creation of Department's undergraduate recruiting brochure 2002
  - Professorial Assistant Recruiter (2001, 2002, 2003)

COLLEGE

- College Representative to University Council/Academic Council 2005-
- Engineering College Research and Graduate Studies Committee (Chair committee) 2005-
- Deans Search Committee, College of Engineering. 1998 – 1999.
- Tenure and Promotion Committee, 1994
- Proctor EIT Exam, 1992, 1994
- Invention Evaluation Committee, 1989-present
- Applied Science Program Committee, 1989-1991
- Coordinator of Student Exchange Program with the Monterrey Institute of Technology, Monterrey, Mexico, 1981-1985
- College Representative to Committee on Libraries, 1982-1986
- Minority Mentoring Program, 1984-1986
- Preview CSU Program (introduction to university for entering freshmen), 1985-1986
- Member of ad hoc committee reporting to the Committee on Academic Programs to evaluate the Agricultural Engineering Program
- Undergraduate Admissions Committee, 1980-1986
- Faculty Advisor to the Student Chapter of the American Institute of Chemical Engineers, 1984-1986

UNIVERSITY

- Faculty Advisor for Guatemalan Students Club, 1994
- Faculty Advisor for Latter-day Saints Student Association, 1997-present
- Member Faculty of Food Science and Technology, 1993-1996
- Member Users Advisory Group, Biotechnology Support Laboratory, 1992
- Committee on Toxic Chemicals, 1990-1996 (Chairman Pro Tem, 1991)
- Faculty Senate ad hoc Committee on the Life Sciences, 1988-1989

- Institute for Food Science and Engineering Planning Committee, 1990
- Toxicology Faculty Executive Committee, 1989-1996
- Executive Committee for Center for Macromolecular Design, 1989-1996
- Search Committee for Director of Libraries, 1985
- Chairman of the Committee on Libraries, 1985
- Conducted University-wide Survey of Priorities for the Library, 1986
- University-wide Grievance Committee (1986)

PUBLIC SERVICE

- President, Lansing Michigan Stake, The Church of Jesus Christ of Latter-day Saints; Oct. 1999 – 2008.
- Bishop, East Lansing University Ward, The Church of Jesus Christ of Latter-day Saints, Oct. 1998 – Oct. 1999
- Director of the Family History Center, Bryan-College Station, Texas, 1994
- Member, Longs Peak Council, Boy Scouts of America, 1986-1988
- Advisor, Explorer Troop 282, Boy Scouts of America, 1984-1986
- Director and Staff Librarian, Family History Library, Ft. Collins, Colorado, 1983-1985

OTHER IMPORTANT ACTIVITIES

Coordinator and lecturer for short course "Industrial Bioprocessing," Colorado State University, August 1984, June 1985, June 1986, June 1987, September 1988, October 1989, October 1990, September 1991, August 1992, September 1993, July 1994.

Fundamentals of Biochemical Engineering, Short Course (29 hours) presented to Stearns-Rogers Corp., Denver, Colorado. January - March 1988.

Co-developer (with Dr. Mark Worden) and lecturer at the short course “Principles of Chemical Engineering for Life Scientists” presented to duPont, Inc. May and August, 2000, March 2001.

Co-chairman (with Jim Liao) of Biotechnology Program Planning (group 15c) for meetings of the American Institute of Chemical Engineers, 1994-1997.

Member of New Technology Committee, American Institute of Chemical Engineers, 1993-2001.

Invited participant (one of two from MSU) to the U. S. Department of Energy's Workshop on Identifying High Potential Crops and Bioproducts. March 7, 2002. Chicago, IL

DECLARATION OF BRUCE E. DALE, Ph.D.

EXHIBIT B

Proximate Causes and Underlying Driving F orces of Tropical Deforestation

HELMUT J. GEIST AND ERIC F. LAMBIN

One of the primary causes of global environmental change is tropical deforestation, but the question of what factors drive deforestation remains largely unanswered (NRC 1999). Various hypotheses have produced rich arguments, but empirical evidence on the causes of deforestation continues to be largely based on cross-national statistical analyses (Bilsborrow 1994, Brown and Pearce 1994, Williams 1994, Painter and Durham 1995, Sponsel et al. 1996, Murali and Hedge 1997, Rudel and Roper 1997, Fairhead and Leach 1998). In some cases, these analyses are based on debatable data on rates of forest cover change (Palo 1999). The two major, mutually exclusive—and still unsatisfactory—explanations for tropical deforestation are single-factor causation and irreducible complexity. On the one hand, proponents of single-factor causation suggest various primary causes, such as shifting cultivation (Amelung and Diehl 1992, Myers 1993, Rerkasem 1996, Ranjan and Upadhyay 1999) and population growth (Allen and Barnes 1985, Amelung and Diehl 1992, Cropper and Griffiths 1994, Ehrhardt-Martinez 1998, Mather and Needle 2000). On the other hand, correlations between deforestation and multiple causative factors are many and varied, revealing no distinct pattern (Rudel and Roper 1996, Bawa and Dayanandan 1997, Mather et al. 1998, Angelsen and Kaimowitz 1999).

In addition to chronicling these attempts to identify general causes of deforestation through global-scale statistical analyses, the literature is rich in local-scale case studies investigating the causes and processes of forest cover change in specific localities. Our aim with this study is to generate from local-scale case studies a general understanding of the proximate causes and underlying driving forces of tropical deforestation while preserving the descriptive richness of these studies. Proximate causes are human activities or immediate actions at the local level, such as agricultural expansion, that originate from intended land use and directly impact forest cover. Underlying driving forces are fundamental social processes, such as human population dynamics or agricultural policies, that underpin the proximate causes and either operate at the local level or have an indirect impact from the national or global level.

TROPICAL FORESTS ARE DISAPPEARING AS THE RESULT OF MANY PRESSURES, BOTH LOCAL AND REGIONAL, ACTING IN VARIOUS COMBINATIONS IN DIFFERENT GEOGRAPHICAL LOCATIONS

We analyzed the frequency of proximate causes and underlying driving forces of deforestation, including their interactions, as reported in 152 subnational case studies. We show that tropical deforestation is driven by identifiable regional patterns of causal factor synergies, of which the most prominent are economic factors, institutions, national policies, and remote influences (at the underlying level) driving agricultural expansion, wood extraction, and infrastructure extension (at the proximate level). Our findings reveal that prior stud-

Helmut Geist (e-mail: geist@geog.ucl.ac.be) is a postdoctoral researcher (geography) in the field of human drivers of global environmental change and executive director of the Land Use and Cover Change (LUCC) core project of the International Geosphere-Biosphere Program (IGBP) and International Human Dimensions Program (IHDP) on Global Environmental Change, LUCC International Project Office, Department of Geography, University of Louvain, Place Louis Pasteur 3, B-1348 Louvain-la-Neuve, Belgium. Eric Lambin is a professor of geography with research interests in remote sensing and human ecology applied to studies of deforestation, desertification, and biomass burning in tropical regions. He is the chair of the IGBP and IHDP core project LUCC at the University of Louvain.

ies have given too much emphasis to population growth and shifting cultivation as primary causes of deforestation.

Data analysis

Case studies of net losses of tropical forest cover ($n = 152$) were analyzed to determine whether the proximate causes and underlying driving forces of tropical deforestation fall into any patterns. Study areas range from a community to a multi-province area, and cases span time periods from 1880 to 1996, with 1940 to 1990 being the most frequently covered period. The 152 cases of tropical deforestation were taken from 95 articles published in 40 journals covered by the citation index of the Institute for Scientific Information (Geist and Lambin 2001). The criteria for selecting studies were the following: quantification of the rates of forest-cover change; net loss of forest cover during at least part of the study period; investigation method based on quantitative data or in-depth field investigations; consideration of clearly named factors as potential causes of deforestation, including basic features of the socioeconomic setting and the natural resource endowment; and absence of obvious disciplinary bias. We assumed that each study revealed the actual causes of deforestation in the study area. Therefore, our comparative analysis of case studies evaluates which causal patterns leading to deforestation are most often found in different tropical regions.

Four broad clusters of proximate causes were identified: agricultural expansion, wood extraction, infrastructure extension, and other factors. Each land use category was further subdivided; for example, agricultural expansion was divided into permanent cultivation, shifting cultivation, cattle ranching, and colonization (Figure 1). Underlying driving forces were categorized into five broad clusters: demographic, economic, technological, policy and institutional, and cultural factors. Each was further subdivided into specific factors; for example, cultural or sociopolitical factors were partitioned into public attitudes, values and beliefs, and individual or household behavior (Figure 1; Ledec 1985, Lambin 1994, Ojima et al. 1994, Turner et al. 1995, Lambin 1997, Contreras-Hermosilla 2000).

Causal factors were quantified by determining the most frequent proximate and underlying factors in each case. The major interactions and feedback processes between these factors were also identified to reveal the systems dynamics that commonly lead to deforestation. Three modes of causation were distinguished: single-factor causation (i.e., one individual underlying factor driving one or more proximate factors), chain-logical causation (i.e., several interlinked factors in combination leading to deforestation), and concomitant occurrence (i.e., independent, separate operation of factors causing deforestation). Results were broken down by broad geographical regions (Asia, $n = 55$; Africa, $n = 19$; Latin America, $n = 78$). They are given in order of decreasing importance, with factors occurring in less than 25% of the cases not reported.

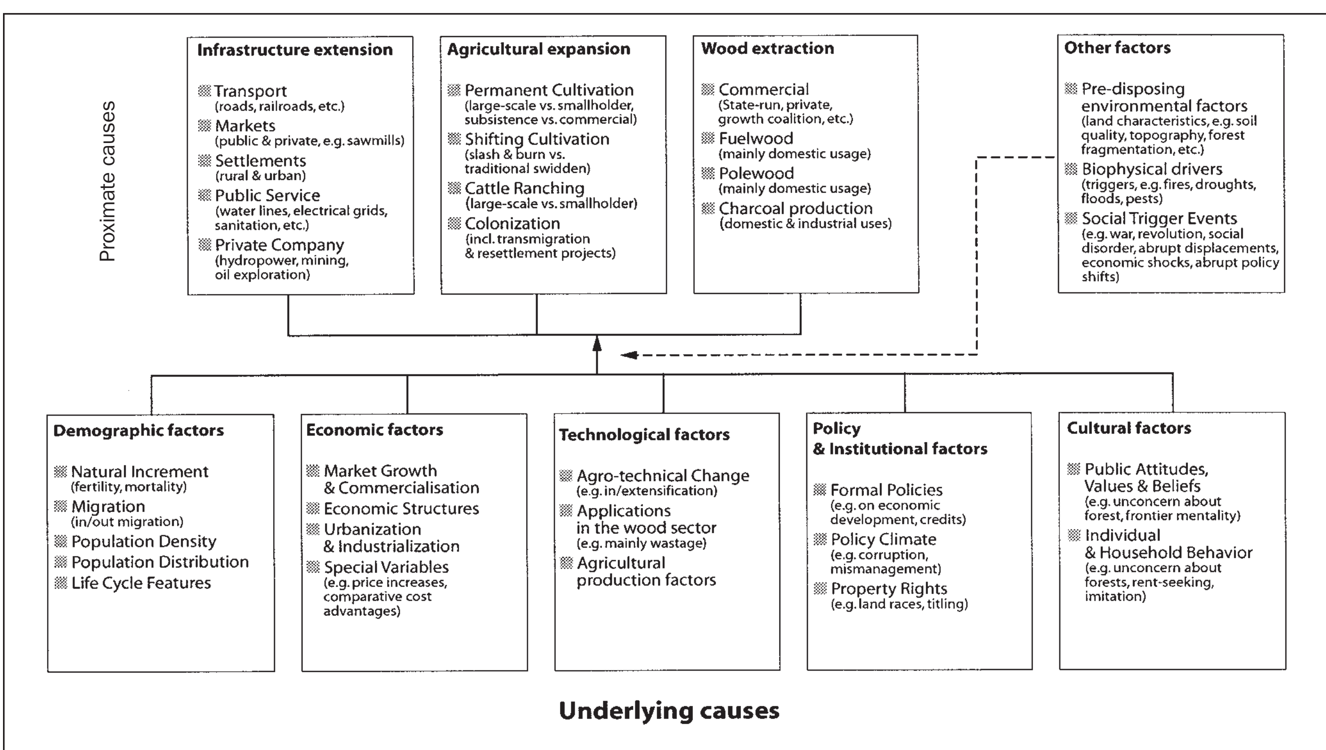

Figure 1. Causes of forest decline. Five broad clusters of underlying driving forces (or fundamental social processes) underpin the proximate causes of tropical deforestation, which are immediate human actions directly impacting forest cover.

Proximate causes

At the proximate level, tropical deforestation is best explained by multiple factors rather than by single variables. Dominating the broad clusters of proximate causes is the combination of agricultural expansion, wood extraction, and infrastructure expansion, with clear regional variations (Table 1). The tables presented here provide a breakdown of proximate causes and underlying driving forces by broad geographical regions (or continents). They show the absolute number as well as the relative percentage of the frequency of causative variables reported in the case studies. Tables 1 and 3 give only the broad clusters of proximate causes and underlying driving forces, and Tables 2 and 4 provide a detailed breakdown of the broad clusters by specific factors. Only the frequency of modes of causation (single or multifactorial) by broad clusters of proximate and underlying variables (Tables 1 and 3) shows cumulative percentages of cases, adding up to 100%. The relative percentages of the frequency of occurrence of specific factors (Tables 2 and 4) do not add up to 100%, as multiple counts exist because of causal factor synergies (discussed later).

Agricultural expansion is, by far, the leading land-use change associated with nearly all deforestation cases (96%). It includes, with more or less equal frequencies, forest conversion for permanent cropping, cattle ranching, shifting cultivation, and colonization agriculture (Table 2). Only permanent agriculture and shifting cultivation display low geographical variation; that is, regional values for permanent cultivation in Asia, Africa, and Latin America are close to the "global" value (i.e., 44%, 53%, and 50%, respectively, compared with a global 48%), similarly for shifting cultivation (i.e., 44%, 42%, and 40%, respectively, compared with a global 41%). Further subdivisions reveal striking regional differences, however. In permanent cultivation, the expansion of food-crop cultivation for subsistence is three times more frequently reported than the expansion of commercial farming (less than 25% for all regions). In shifting cultivation, cases of deforestation driven by slash-and-burn agriculture are more widespread in upland and foothill zones of Asia than elsewhere, whereas when practiced by colonizing migrant settlers in Latin America, it is mainly limited to lowland areas. Pasture creation for cattle ranching is a striking cause of deforestation reported almost exclusively for humid lowland cases from mainland South America.

Commercial wood extraction is frequent in both mainland and insular Asia, whereas in Africa the harvesting of fuel wood and poles by individuals for domestic uses dominates cases of deforestation associated with wood extraction. Among all forms of infrastructure expansion, road construction is by far most frequently reported, mainly in both lowland and mountain cases of Latin America. Predisposing environmental factors such as land characteristics (soil quality, topography) or trigger events, whether biophysical (droughts,

Table 1. Frequency of broad clusters of proximate causes in tropical deforestation.

	All cases (*n* = 152)			Asia (*n* = 55)		Africa (*n* = 19)		Latin America (*n* = 78)	
	abs	rel (%)	cum (%)	abs	rel (%)	abs	rel (%)	abs	rel (%)
Single-factor causation									
Agricultural expansion	6	4	4	2	4	1	5	3	4
Wood extraction	2	1	5	0	–	2	11	0	–
Infrastructure expansion	1	1	6	0	–	0	–	1	1
Other[a]	0	–	–	0	–	0	–	0	–
Two-factor causation									
Agro-wood[b]	22	15	20	12	22	2	11	8	10
Agro-infra[c]	30	20	40	3	6	2	11	25	32
Agro-other	5	3	43	1	2	3	16	1	1
Wood-infra	1	1	44	0	–	0	–	1	1
Wood-other	1	1	45	0	–	1	6	0	–
Three-factor causation									
Agro-wood-infra	38	25	70	21	38	2	11	15	19
Agro-wood-other	6	4	74	4	7	1	5	1	1
Agro-infra-other	8	5	79	0	–	0	–	8	10
Wood-infra-other	1	1	80	0	–	0	–	1	1
Four-factor causation									
All	31	20	100	12	22	5	26	14	18
Total	152	100	–	55	100	19	100	78	100

Note: abs, absolute number; rel, relative percentages; cum, cumulative percentages. Relative percentages may not total 100 because of rounding.
a. "Other" refers to predisposing environmental factors, such as land characteristics and social as well as biophysical trigger events.
b. Agro, agricultural expansion; wood, wood extraction.
c. Infra, infrastructure expansion.

floods) or social (mainly wars), are reported to influence deforestation in one-third of the cases.

Among the detailed categories of proximate causes for all regions, the extension of overland transport infrastructure, followed by commercial wood extraction, permanent cultivation, and cattle ranching, are the leading proximate causes of deforestation. Contrary to widely held views, case study evidence suggests that shifting cultivation is not the primary cause of deforestation.

Underlying driving forces

At the underlying level, tropical deforestation is also best explained by multiple factors and drivers acting synergistically rather than by single-factor causation, with more than one-third of the cases being driven by the full interplay of economic, institutional, technological, cultural, and demographic variables (Table 3).

Economic factors are prominent underlying forces of tropical deforestation (81%). Commercialization and the growth of mainly timber markets (as driven by national and international demands) as well as market failures are frequently reported to drive deforestation (Table 4). Economic variables such as low domestic costs (for land, labor, fuel, or timber), product price increases (mostly for cash crops), and the ecological footprint of remote urban-industrial centers underpin about one-third of the cases each, whereas the requirement to generate foreign exchange earnings at a national level intervenes in a quarter of the cases. With few exceptions, factors related to economic development through a growing cash economy show little regional variation and, thus, constitute a robust underlying force of deforestation. A number of case studies describe a process of frontier colonization with a sequence of poverty- and capital-driven deforestation (Rudel and Roper 1997). Poverty-driven deforestation refers to the ecological marginalization of farmers who have lost their resource entitlements, and capital-driven deforestation refers to public or private investments to develop the frontier for political, economic, or social reasons. Underlying 42% of the cases each, both processes overlap considerably.

Institutional factors also drive many cases of deforestation (78%). These factors mainly include formal pro-deforestation measures such as policies on land use and economic development as related to colonization, transportation, or subsidies for land-based activities. Land tenure arrangements and policy failures (such as corruption or mismanagement in the forestry sector) are also important drivers of deforestation. Though much discussed as a general cause of deforestation (e.g., Deacon 1994, Mendelsohn and Balick 1995), property rights issues are mainly a characteristic of Asian cases and tend to have ambiguous effects upon forest cover: insecure ownership, quasi-open access conditions, maladjusted customary rights, as well as the legalization of land titles, are all reported to influence deforestation in a similar manner.

Among technological factors (70%), important processes affecting deforestation are agrotechnological change, with agricultural intensification having no distinct impact separate from agricultural expansion, and poor technological applications in the wood sector (leading to wasteful logging practices).

Table 2. Frequency of specific proximate causes in tropical deforestation.

	All cases (*n* = 152)		Asia (*n* = 55)		Africa (*n* = 19)		Latin America (*n* = 78)	
	abs	rel (%)	abs	rel (%)	abs	rel (%)	abs	rel (%)
Agricultural expansion	146	96	55	100	16	84	75	96
Permanent cultivation	73	48	24	44	10	53	39	50
Subsistence agriculture	61	40	20	36	10	53	31	40
Cattle ranching	70	46	3	6	3	16	64	82
Shifting cultivation	63	41	24	44	8	42	31	40
Swidden agriculture	46	30	24	44	7	37	15	19
Colonization[a]	61	40	23	42	4	21	34	44
Infrastructure expansion	110	72	36	66	9	47	65	83
Transport extension	97	64	26	47	9	47	62	80
Roads	93	61	25	46	9	47	59	76
Settlement/market extension	41	27	12	22	3	16	26	33
Wood extraction	102	67	49	89	13	68	40	51
Commercial (for trade)	79	52	43	78	5	26	31	40
Fuel wood (for domestic uses)	42	28	18	33	10	53	14	18
Other factors[b]	52	34	17	31	10	53	25	32

Note: Multiple counts possible; percentages relate to the total of all cases for each category; abs, absolute number; rel, relative percentages; cum, cumulative percentages. Relative percentages may not total 100 because of rounding.

a. Including transmigration and resettlement.

b. Predisposing environmental factors such as land characteristics and social or biophysical trigger events.

Table 3. Frequency of broad underlying driving forces in tropical deforestation.

	All cases (n = 152)			Asia (n = 55)		Africa (n = 19)		Latin America (n = 78)	
	abs	rel (%)	cum (%)	abs	rel (%)	abs	rel (%)	abs	rel (%)
Single-factor causation									
Economic (econ)	13	9	9	0	–	0	–	13	17
Institutional (inst)	4	3	12	0	–	1	5	3	4
Technological (tech)	0	–	12	0	–	0	–	0	–
Cultural (cult)	0	–	12	0	–	0	–	0	–
Demographic (pop)	0	–	12	0	–	0	–	0	–
Two-factor causation									
Pop-econ	5	3	15	0	–	3	16	2	3
Pop-tech	4	3	17	2	4	1	6	1	1
Pop-inst	1	1	18	0	–	0	–	1	1
Pop-cult	1	1	18	0	–	0	–	1	1
Econ-tech	1	1	19	0	–	0	–	1	1
Econ-inst	5	3	22	0	–	0	–	5	6
Inst-cult	5	3	26	4	7	0	–	1	1
Three-factor causation									
Pop-econ-tech	5	3	29	0	–	4	21	1	1
Pop-econ-inst	1	1	30	1	2	0	–	0	–
Pop-econ-cult	2	1	31	0	–	1	5	1	1
Pop-tech-inst	4	3	34	1	2	1	5	2	3
Econ-tech-cult	1	1	34	0	–	0	–	1	1
Econ-inst-cult	6	4	38	0	–	0	–	6	8
Tech-inst-cult	5	3	42	5	9	0	–	0	–
Four-factor causation									
Pop-econ-tech-inst	8	5	47	5	9	2	11	1	1
Pop-econ-tech-cult	1	1	47	0	–	1	5	0	–
Pop-econ-inst-cult	2	1	49	1	2	0	–	1	1
Pop-tech-inst-cult	5	3	52	4	7	0	–	1	1
Econ-tech-inst-cult	19	13	64	12	22	0	–	7	9
Five-factor causation									
All	54	36	100	20	36	5	26	29	37
Total	152	100	–	55	100	19	100	78	100

Note: abs, absolute number; rel, relative percentages; cum, cumulative percentages. Relative percentages may not total 100 because of rounding.

Cultural or sociopolitical factors (66%) are reported to underlie mainly economic and policy forces in the form of attitudes of public unconcern towards forest environments. These factors also shape the rent-seeking behavior of individual agents causing deforestation.

Among demographic factors (61%), only in-migration of colonizing settlers into sparsely populated forest areas, with the consequence of increasing population density there, shows a notable influence on deforestation. It tends to feature African and Latin American rather than Asian cases. Contrary to a common misconception, population increase due to high fertility rates is not a primary driver of deforestation at a local scale, over a time period of a few decades, as it intervenes in 8% of the cases only and is always combined with other factors.

Interactions and feedbacks

Not only are multiple causal factors at work, but their interactions also lead to deforestation, which is why it is important to understand the systems dynamics (Figure 2). Our analysis reveals that, in most cases, three to four underlying causes are driving two to three proximate causes. A frequent pattern of causal interaction stems from the necessity for road construction that is associated with wood extraction or agricultural expansion, which is mostly driven by policy and institutional factors but also by economic and cultural factors. Pro-deforestation state policies aimed at land use and economic development (e.g., credits, low taxation, incentives for cash cropping, legal land titling) lead to the expansion of commercial crops and pastures in combination with an extension of the road network. Another pattern, seen mostly in Africa, comes from insecure ownership related to uncertainties of land tenure, which drives the shift from communal to private property and underlies many cases in which traditional shifting cultivation is a direct cause of deforestation. Policies facilitating the establishment of state agricultural and forestry plantations lead to deforestation in both insular and continental Asia. Agricultural colonization in Latin America is

Table 4. Frequency of specific underlying driving forces in tropical deforestation.

	All cases (n = 152)		Asia (n = 55)		Africa (n = 19)		Latin America (n = 78)	
	abs	rel (%)	abs	rel (%)	abs	rel (%)	abs	rel (%)
Economic factors	123	81	39	71	16	84	68	87
Market growth/commercialization	103	68	30	55	15	79	58	74
Sectoral market growth[a]	78	51	23	42	13	68	42	54
Demand/consumption[b]	69	45	24	44	13	68	32	41
Market failures	52	34	22	40	6	32	24	31
Urban-industrial growth	58	38	23	42	5	26	30	39
Industrialization	43	28	21	38	1	5	21	27
Foreign exchange[c]	38	25	16	29	5	26	17	22
Special variables[d]	48	32	9	16	5	26	34	44
Institutional/policy factors	119	78	53	96	9	47	57	73
Formal policies	105	69	46	84	7	37	52	67
On land development	60	40	28	51	5	26	27	35
On economic growth[e]	51	34	22	40	5	26	24	31
On credits/subsidies	39	26	11	20	1	5	27	35
Property rights issues[f]	67	44	33	60	5	26	29	37
Policy failures[g]	64	42	31	56	1	5	32	41
Mismanagement	38	25	13	24	1	5	24	31
Technological factors	107	70	49	89	14	74	44	56
Agrotechnological change[h]	70	46	28	51	8	42	34	44
Production changes	50	33	17	31	5	26	28	36
Wood sector related[i]	69	45	39	71	8	42	22	28
Agriculture related	42	28	22	40	4	21	16	21
Cultural/sociopolitical factors	101	66	46	84	7	37	48	62
Public attitudes, values, beliefs	96	63	45	82	5	26	46	59
Public unconcern[j]	66	43	25	46	3	16	38	49
Missing basic values	55	36	33	60	2	11	20	26
Individual/household behavior	80	53	38	69	6	32	36	46
Situation specific[k]	74	49	36	66	5	26	33	42
Unconcern by individuals[l]	48	32	20	36	4	21	24	31
Demographic factors[m]	93	61	34	62	18	95	41	53
In-migration	58	38	12	22	9	47	37	47
Growing population density	38	25	12	22	6	32	20	26

Note: Multiple counts possible; percentages relate to the total of all cases in each category; abs, absolute number; rel, relative percentages; cum, cumulative percentages. Relative percentages may not total 100 because of rounding.

a. Growth of markets for wood (e.g., timber products) 29%, agricultural products (e.g., food) 29%, and minerals 15% (e.g., oil energy).

b. Demand for wood (e.g., processed timber) 32% and agricultural products (e.g., food) 18%.

c. Generation of foreign exchange earnings.

d. Low cost conditions (production factors) and price changes (increases and decreases).

e. Especially agricultural and infrastructure development policies.

f. "Land races," land tenure insecurity, quasi open access conditions, maladjusted customary rights, titling/legalization, low empowerment of local user groups.

g. Corruption, lawlessness, clientelism, and the operation of vested interests and "growth coalitions," besides mismanagement or poor performance.

h. Land use intensification and extension, besides changes in market vs. subsistence orientation, in intensity of labor vs. capital used, and in holding size (productional changes).

i. Poor logging performance, wastage in timber processing, and poor domestic or industrial furnace performance.

j. Dominant frontier mentality, prevailing attitudes of nation-building, modernization, and development, and low (public) morale.

k. Mainly rent-seeking behavior (35%).

l. Unconcern about the forest environment as reflected in increasing levels of demand, aspiration, and consumption, commonly associated with increased income.

m. Including natural increment, spatial distribution, and life cycle features.

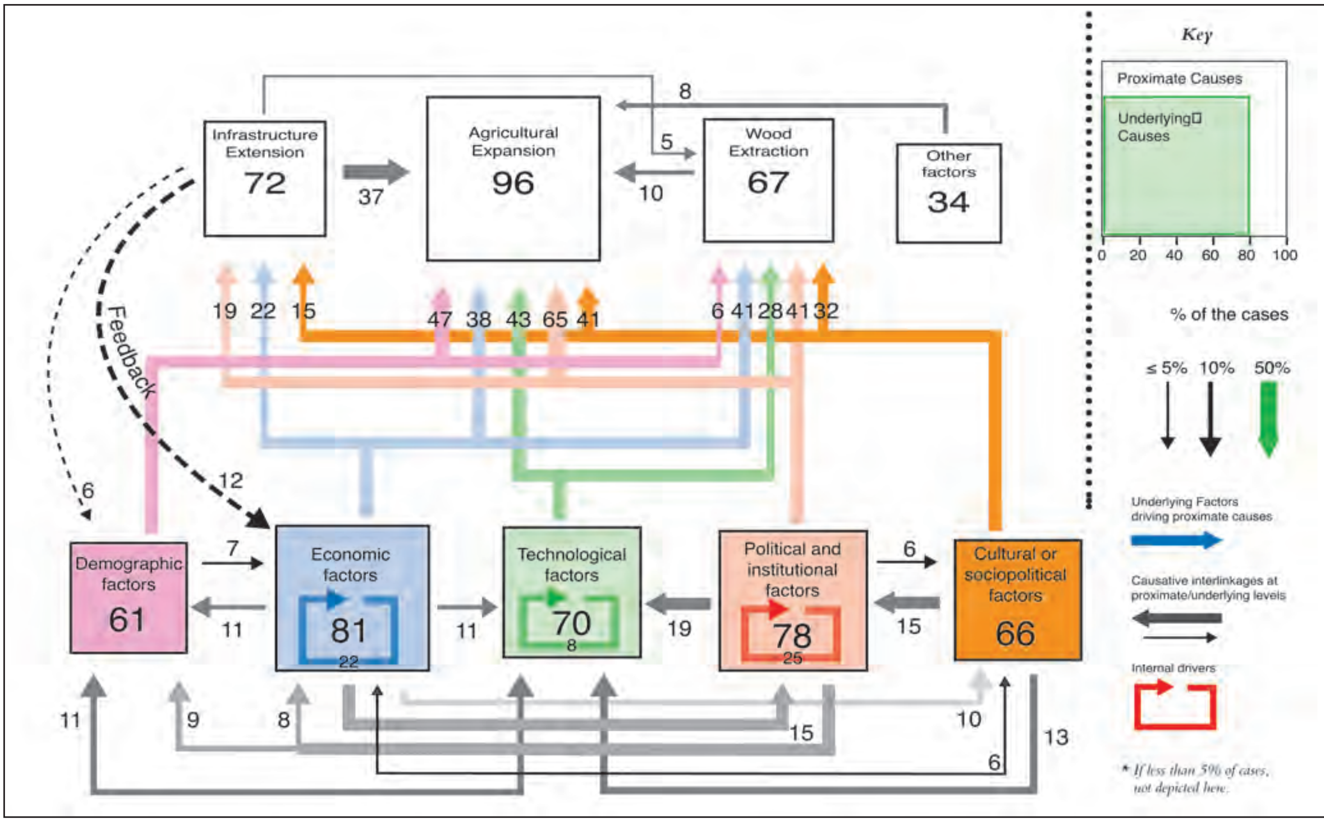

Figure 2. Causative pattern of tropical deforestation (*n *= 152 cases). Systems dynamics commonly lead to tropical deforestation. No single or key variable, such as population growth or shifting cultivation, unilaterally impacts forest cover change; synergies between proximate causes and underlying (social) driving forces best explain tropical forest cover losses. A recurrent set of mainly economic, political, and institutional driving forces underpins proximate causes, such as agricultural expansion, infrastructure extension, and wood extraction, leading to deforestation. Though some investigators have claimed irreducible complexity is the explanation, distinct regional patterns exist.

often favored by land policies that are directed towards deregulation of land access, transfer of public forest land to private holdings, and state regulations in favor of large individual land holdings.

Policy, institutional, and economic factors are also driving wood extraction. Cases of deforestation related to both private and state-run timber logging, especially in Asia, are almost exclusively driven by the liberal granting of concessions, development projects, and state claims for logging areas, in conjunction with corruption and poor implementation of forestry rules.

In-migration and, to a much lesser degree, natural population growth drive the expansion of cropped land and pasture in 47% of the cases in Africa and Latin America (22% in Asia), concomitantly with other underlying drivers. The extension of permanently cropped land for subsistence farming to meet the needs of a growing population is reported particularly for African cases. Expansion of pastures emerges exclusively from mainland South American cases, in association with processes of both planned colonization and spontaneous settlement by colonist agriculturalists.

Some feedbacks amplify the process of deforestation. The most frequent feedback identified is that from road construction and the creation of new settlements in a frontier area, which work upon economic factors such as the growth of wood and food markets. The development of commercialization induces further deforestation and agricultural modernization, mainly in frontier regions of the Amazon lowlands and in southeast Asia. Shifting cultivators turn into sedentary cash croppers and permanently settled subsistence farmers who respond to market signals.

Conclusion

Evidence from empirical case studies that identify both proximate causes and underlying forces of tropical deforestation suggests that no universal link between cause and effect exists. Rather than providing support for dominant theories of global deforestation (neoclassical, impoverishment, political ecology), analysis of these studies shows that tropical forest decline is determined by different combinations of various proximate causes and underlying driving forces in varying geographical and historical contexts. Some of these combinations are robust geographically (such as the development of market economies and the expansion of permanently cropped land for food), whereas most of them are region specific. The observed causal factor synergies challenge single-factor explanations that put most of the blame of deforestation upon shifting cultivators and population growth (caused by natural increment). Rather, our analysis reveals that, at the underlying level, public and individual decisions largely respond to changing, national- to global-scale economic opportunities and/or policies, as mediated by local-scale institutional factors, and that, at the proximate level, regionally distinct modes of agricultural expansion, wood extraction, and infrastructure extension prevail in causing deforestation. As a major implication, case study–based evidence reveals that no universal policy for controlling tropical deforestation can be conceived. Rather, a detailed understanding of the complex set of proximate causes and underlying driving forces affecting forest cover changes in a given location is required prior to any policy intervention.

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EXHIBIT C

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DYNAMICS OF LAND-USE AND LAND-COVER CHANGE IN TROPICAL REGIONS

Eric F. Lambin,[1] Helmut J. Geist,[2] and Erika Lepers[2]
[1]*Department of Geography, University of Louvain, Place Louis Pasteur 3, B-1348 Louvain-la-Neuve, Belgium; email: lambin@geog.ucl.ac.be*
[2]*LUCC International Project Office, Department of Geography, University of Louvain, Place Louis Pasteur 3, B-1348 Louvain-la-Neuve, Belgium; email: geist@geog.ucl.ac.be, lepers@geog.ucl.ac.be*

Key Words deforestation, agriculture, urbanization, land degradation, landscape

■ **Abstract** We highlight the complexity of land-use/cover change and propose a framework for a more general understanding of the issue, with emphasis on tropical regions. The review summarizes recent estimates on changes in cropland, agricultural intensification, tropical deforestation, pasture expansion, and urbanization and identifies the still unmeasured land-cover changes. Climate-driven land-cover modifications interact with land-use changes. Land-use change is driven by synergetic factor combinations of resource scarcity leading to an increase in the pressure of production on resources, changing opportunities created by markets, outside policy intervention, loss of adaptive capacity, and changes in social organization and attitudes. The changes in ecosystem goods and services that result from land-use change feed back on the drivers of land-use change. A restricted set of dominant pathways of land-use change is identified. Land-use change can be understood using the concepts of complex adaptive systems and transitions. Integrated, place-based research on land-use/land-cover change requires a combination of the agent-based systems and narrative perspectives of understanding. We argue in this paper that a systematic analysis of local-scale land-use change studies, conducted over a range of timescales, helps to uncover general principles that provide an explanation and prediction of new land-use changes.

CONTENTS

INTRODUCTION

Concerns about land-use/cover change emerged in the research agenda on global environmental change several decades ago with the realization that land surface processes influence climate. In the mid-1970s, it was recognized that land-cover change modifies surface albedo and thus surface-atmosphere energy exchanges, which have an impact on regional climate (1–3). In the early 1980s, terrestrial ecosystems as sources and sinks of carbon were highlighted; this underscored the impact of land-use/cover change on the global climate via the carbon cycle (4, 5). Decreasing the uncertainty of these terrestrial sources and sinks of carbon remains a serious challenge today. Later, the important contribution of local evapotranspiration to the water cycle—that is precipitation recycling—as a function of land cover highlighted yet another considerable impact of land-use/cover change on climate, at a local to regional scale in this case (6).

A much broader range of impacts of land-use/cover change on ecosystem goods and services were further identified. Of primary concern are impacts on biotic diversity worldwide (7), soil degradation (8), and the ability of biological systems to support human needs (9). Land-use/cover changes also determine, in part, the vulnerability of places and people to climatic, economic, or sociopolitical perturbations (10). When aggregated globally, land-use/cover changes significantly affect central aspects of earth system functioning. All impacts are not negative though, as many forms of land-use/cover changes are associated with continuing increases in food and fiber production, in resource use efficiency, and in wealth and well-being.

Understanding and predicting the impact of surface processes on climate required long-term historical reconstructions and projections into the future of land-cover changes at regional to global scales (11, 12). Quantifying the contribution of terrestrial ecosystems to global carbon pools and flux required accurate mapping of land cover and measurements of land-cover conversions worldwide (13–15). Fine resolution, spatially explicit data on landscape fragmentation were required to understand the impact of land-use/cover changes on biodiversity (16, 17). Predicting how land-use changes affect land degradation, the feedback on livelihood strategies from land degradation, and the vulnerability of places and people in the face of land-use/cover changes requires a good understanding of the dynamic human-environment interactions associated with land-use change (10).

Over the last few decades, numerous researchers have improved measurements of land-cover change, the understanding of the causes of land-use change, and predictive models of land-use/cover change, in part under the auspices of the Land-Use and Land-Cover Change (LUCC) project of the International Geosphere-Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP) (18, 19). Many scientists, especially in the natural sciences, previously assumed that generating local- to global-scale projections of land change several centuries into the past and about 100 years into the future would be easy. Actually, many thought land changes consisted mostly in the conversion of pristine forests to agricultural uses (deforestation) or the destruction of natural vegetation by overgrazing, which leads to desert conditions (desertification). These conversions were assumed to be irreversible and spatially homogeneous and to progress linearly. Only the growth of the local population and, to a lesser extent, its increase in consumption were thought to drive the changes in land conditions.

Recent research has largely dispelled these simplifications and replaced them by a representation of much more complex, and sometimes intricate, processes of land-use/cover change. A consensus is progressively being reached on the rate and location of some of the main land changes, but other forms of change, such as desertification, are still unmeasured and controversial. Understanding of the causes of land-use change has moved from simplistic representations of two or three driving forces to a much more profound understanding that involves situation-specific interactions among a large number of factors at different spatial and temporal scales. The richness of explanations has greatly increased, often at the expense of generality of the explanations. Today, only a very few models of land-use change can generate long-term, realistic projections of future land-use/cover changes at regional to global scales. The last decade, however, has witnessed innovative methodological developments in the modeling of land-use change at local to regional scales (20–22). Nevertheless, the recent progress in our understanding of the causes of land-use change still has to be fully integrated in models of the process.

This review describes how our understanding of land-use/cover change has moved from simplicity to greater realism and complexity over the last decades. The main emphasis of the review is on tropical regions. Our goal is to extract from this complexity a general framework for a more general understanding of land-use/cover change. First, the most recent estimates of the magnitude of land-use/cover change are summarized. Second, the complex nature of land-cover change is discussed to emphasize the need to integrate all scales and processes of change. Third, a synthesis of recent case study evidence on the causes of land-use change is presented, with emphasis on the mode of interaction between diverse causes and dominant pathways of change. Fourth, the complexity of land-use change is described using the notions of complex adaptive systems and transition. Integrative perspectives to analyze land-use/cover changes are then discussed. The review highlights the dynamic nature of coupled human-environment systems in relation to land-use/cover change.

RECENT ESTIMATES OF GLOBAL LAND-USE/COVER CHANGE

Historical Changes

Since humans have controlled fire and domesticated plants and animals, they have cleared forests to wring higher value from the land. About half of the ice-free land surface has been converted or substantially modified by human activities over the last 10,000 years. A recent study estimated that undisturbed (or wilderness) areas represent 46% of the earth's land surface (23). Forests covered about 50% of the earth's land area 8000 years ago, as opposed to 30% today (24). Agriculture has expanded into forests, savannas, and steppes in all parts of the world to meet the demand for food and fiber. Agricultural expansion has shifted between regions over time; this followed the general development of civilizations, economies, and increasing populations (25).

Two recent studies estimated historical changes in permanent cropland at a global scale during the last 300 years by spatializing historical cropland inventory data based on a global land-cover classification derived by remote sensing, which used a hindcasting approach (11), or based on historical population density data (26). The area of cropland has increased globally from an estimated 300–400 million ha in 1700 to 1500–1800 million ha in 1990, a 4.5- to fivefold increase in three centuries and a 50% net increase just in the twentieth century. The area under pasture—for which more uncertainties remain—increased from around 500 million ha in 1700 to around 3100 million ha in 1990 (27). These increases led to the clearing of forests and the transformation of natural grasslands, steppes, and savannas. Forest area decreased from 5000–6200 million ha in 1700 to 4300–5300 million ha in 1990. Steppes, savannas, and grasslands also experienced a rapid decline, from around 3200 million ha in 1700 to 1800–2700 million ha in 1990 (11, 26) (Table 1).

Europe, the Indo-Gangetic Plain, and eastern China experienced first the most rapid cropland expansion during the eighteenth century. Starting in the nineteenth century, the newly developed regions of North America and the former Soviet Union followed suit. China experienced a steady rate of expansion throughout the last three centuries (28). A very gradual cropland expansion occurred in Africa, south and Southeast Asia, Latin America, and Australia until 1850, but since then,

TABLE 1 Historical changes in land use/cover at a global scale over the last 300 years (11, 26, 27)

	Forest/woodland (10^6 ha)	Steppe/savanna/grassland (10^6 ha)	Cropland (10^6 ha)	Pasture (10^6 ha)
1700	5000 to 6200	3200	300 to 400	400 to 500
1990	4300 to 5300	1800 to 2700	1500 to 1800	3100 to 3300

these regions have experienced dramatic increases in cropland, especially during the second half of the twentieth century. The greatest cropland expansion in the twentieth century occurred in south and Southeast Asia (28). The Corn Belt in the United States, the prairie provinces in Canada, the pampas grassland region in Argentina, and, a few decades later, southeast Brazil have also seen rapid expansion of permanent cropland early in the twentieth century (28).

Most Rapid Land-Cover Changes of the Last Decades

RECENT FOREST-COVER CHANGES Deforestation occurs when forest is converted to another land cover or when the tree canopy cover falls below a minimum percentage threshold—10% for the United Nations (U.N.) Food and Agriculture Organization (F.A.O.) (29). On the basis of national statistics, inventory reports, estimates by experts, and a pantropical remote sensing survey for tropical forests only, the Global Forest Resources Assessment 2000 (29) estimated that the world's natural forests decreased by 16.1 million hectares per year on average during the 1990s; that is a loss of 4.2% of the natural forest that existed in 1990. However, some natural forests were converted to forest plantations. Gains in forest cover arose from afforestation on land previously under nonforest land use (1.6 million hectares per year globally) and the expansion of natural forests in areas previously under agriculture, mostly in western Europe and eastern North America (3.6 million hectares per year globally). The net global decrease in forest area was therefore 9.4 million hectares per year from 1990 to 2000 (29). The total net forest change for the temperate regions was positive, but it was negative for the tropical regions.

FAO estimated that tropical regions lost 15.2 million hectares of forests per year during the 1990s. Recent estimates for only the world's humid tropical forests (30), based on a sampling strategy of remote sensing data, revised downward by 23% FAO's net rate of change in forest cover for the humid tropics, which exclude tropical dry forests. According to Achard et al. (30), between 1990 and 1997, 5.8 $\pm$ 1.4 million hectares of humid tropical forest were lost each year (Table 2). Forest regrowth accounted for 1.0 $\pm$ 0.32 million hectares. The annual rate of net cover change in humid tropical forest was 0.43% during that period. A further 2.3 $\pm$ 0.7 million hectares of forest were visibly degraded. This figure does not include forests affected by selective logging. Southeast Asia has experienced the highest

TABLE 2 Mean annual change estimates of humid tropical forest cover during the 1990–1997 period[a]

	Forest cover in 1990 (10^6 ha)	Annual net cover change		Annual deforestation		Annual forest regrowth		Annual forest degradation	
		10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%
Latin America	669 ± 57	−2.2 ± 1.2	0.33	2.5 ± 1.4	0.38	0.28 ± 0.22	0.04	0.83 ± 0.67	0.13
Africa	198 ± 13	−0.71 ± 0.31	0.36	0.85 ± 0.30	0.43	0.14 ± 0.11	0.07	0.39 ± 0.19	0.21
Southeast Asia	283 ± 31	−2.0 ± 0.8	0.71	2.5 ± 0.8	0.91	0.53 ± 0.25	0.19	1.1 ± 0.44	0.42
Global	1150 ± 54	−4.9 ± 1.3	0.43	5.8 ± 1.4	0.52	1.0 ± 0.32	0.08	2.3 ± 0.71	0.2

[a]Abstracted with permission from Achard F, Eva HD, Stibig HJ, Mayaux P, Gallego J, et al. 2002. Determination of deforestation rates of the world's humid tropical forests. *Science* 297:999–1002. Copyright 2002 American Association for the Advancement of Science, http://www.sciencemag.org.

rate of net cover change (0.71% per year), whereas Africa and Latin America present lower rates (respectively 0.36% and 0.33%). Latin America, however, lost about the same area of forest as Southeast Asia during the 1990–1997 time period (30). Forest degradation was most extensive in Southeast Asia (0.42% per year), lowest in Latin America (0.13% per year), and intermediate in Africa (0.21% per year). Forest regrowth was more extensive, both in absolute and relative terms, in Southeast Asia than in the other humid tropical regions (0.19% for Southeast Asia, 0.04% for Latin America, and 0.07% for Africa) (30).

These recent assessments of deforestation, as well as another remote sensing survey at a coarser spatial resolution but covering the entire tropical belt (31), concur to estimate less deforestation in the 1990s than was observed in the 1980s. Still, it is unlikely that deforestation has significantly slowed down, because differences in methods of assessment and definitions used may account for at least part of the difference (32). Moreover, deforestation in the dry tropical forests may often be underestimated.

In Latin America, large-scale forest conversion and colonization for livestock-based agriculture is prevalent, whereas cropland expansion by smallholders dominates in Africa. In Asia, intensified shifting agriculture, including migration into new areas, gradual change of existing areas toward more permanent agriculture, and logging explain most of the deforestation (29, 30, 33). Within these regions, deforestation is largely confined to a few areas undergoing rapid change, with annual rates of deforestation from 2% to 5% (Figure 1). The largest deforestation front is the *arc of deforestation* of the Brazilian Amazon, which extends more recently outside Brazil, east of the Andes, and along the road from Manaus to Venezuela. More scattered areas of forest loss are detected in the Chaco and Atlantic forest areas in South America. Central America has significant deforestation fronts in the Yucatán and at the Nicaraguan border with Honduras and Costa Rica. In Africa, forest-cover change is very rapid in Madagascar, Côte d'Ivoire, and the Congo basin, in small scattered hot spots. In Southeast Asia several deforestation fronts are found around Sumatra, Borneo, Vietnam, Cambodia, and Myanmar.

RECENT CHANGES IN AGRICULTURAL AREAS Historically, humans have increased agricultural output mainly by bringing more land into production. The greatest concentration of farmland is found in Eastern Europe, with more than half of its land area in crop cover (28). In the United Kingdom, about 70% of its area is classified as agricultural land (cropland, grassland/rough grazing), with agriculture and areas set aside for conservation or recreation intimately intertwined (37). Despite claims to the contrary, the amount of suitable land remaining for crops is very limited in most developing countries (38, 39), where most of the growing food demand originates. Where there is a large surplus of cultivable land, land is often under rain forest or in marginal areas (38, 39).

The period after 1960 has witnessed a decoupling between food production increase and cropland expansion (Table 3). The 1.97-fold increase in world food production from 1961 to 1996 was associated with only a 10% increase of land under cultivation but also with a 1.68-fold increase in the amount of irrigated cropland and a 6.87- and 3.48-fold increase in the global annual rate of nitrogen and phosphorus fertilization (40). In 2000, 271 million ha were irrigated (25). Globally, the cropland area per capita decreased by more than half in the twentieth century, from around 0.75 ha per person in 1900 to only 0.35 hectare per person in 1990 (28). Note, however, that national statistics in developing countries often substantially underreport agricultural land area (28, 38), e.g., by as much as 50% in parts of China (41).

The mix of cropland expansion and agricultural intensification has varied geographically (25). Tropical Asia increased its food production mainly by increasing

TABLE 3 Increase in world food production and agricultural inputs from 1961 to 1996, based on FAO data (40)

	Number-fold increase in 35 years (1961–1996)
World food production	1.97
Land under cultivation	1.098
Proportion of irrigated land	1.68
Nitrogen fertilization	6.87
Phosphorus fertilization	3.48

fertilizer use and irrigation. Most of Africa and Latin America increased their food production through both agricultural intensification and extensification. Western Africa is the only part of the world where, overall, cropland expansion was accompanied by a decrease in fertilizer use (−1.83% per year) and just a slight increase in irrigation (0.31% per year compared to a world average of 1.22% per year). In 1995, the global irrigated areas were distributed as 68% in Asia, 16% in the Americas, 10% in Europe, 5% in Africa, and 1% in Australia (42). In western Europe and the northeastern United States, cropland decreased during the last decades, after abandonment of agriculture or, in a few cases, following land degradation mostly on marginal land. Globally, this change has freed 222 million ha from agricultural use since 1900 (28).

RECENT CHANGES IN PASTORAL AREAS Natural vegetation covers have given way not only to cropland but also to *pasture*—defined as land used permanently for herbaceous forage crops, either cultivated or growing wild (25). The distinction between pasture and natural savannas or steppes is not always clear. Most pastures are located in Asia (33%) and Africa (28%), with only a small portion being located in Europe and North America (7%) (25). During the last decade, pastures increased considerably in nontropical Asia (at an annual rate of 4.78%), whereas data suggest that pasture land has apparently decreased in eastern Africa. As eastern Africa recorded a large increase in head of cattle over this period [872,000 additional head of cattle per year between 1992 and 1999, according to FAO (25)], it is likely that many areas in pastoral use in Africa are classified as natural vegetation.

RECENT CHANGES IN URBANIZATION In 2000, towns and cities sheltered more than 2.9 billion people, nearly half of the world population (43). Urban population has been growing more rapidly than rural population worldwide, particularly in developing countries. According to the U.N. Population Division (43), the number of megacities, defined here as cities with more than 10 million inhabitants, has changed from one in 1950 (New York) to 17 in 2000, the majority of which are in developing countries. Urban form and function have also changed rapidly. Built-up or paved-over areas are roughly estimated to occupy from 2% to 3% of the earth's land surface (38, 44). For example, in 1997, the 7 million inhabitants of Hong Kong were supported on as little as 120 km^2 of built-up land (45). However, urbanization affects land in rural areas through the *ecological footprint* of cities. This footprint includes, but is not restricted to, the consumption of prime agricultural land in peri-urban areas for residential, infrastructure, and amenity uses, which blurs the distinction between cities and countryside, especially in western developed countries. Urban inhabitants within the Baltic Sea drainage, for example, depend on forest, agriculture, wetland, lake, and marine systems that constitute an area about 1000 times larger than that of the urban area proper (46). In 1997, total nonfood material resources consumed in Hong Kong (i.e., its urban material metabolism) were nearly 25 times larger than the total material turnover of the natural ecosystem. Fossil fuel energy consumed in this city (i.e., its urban energy metabolism) exceeded photosynthetically fixed solar energy by 17 times (45). Time series of global maps of nighttime lights detected by satellite (47) illustrate the rapid changes in both urban extent and electrification of the cities and their surroundings. A question still being debated is whether urban land use is more efficient than rural land use and, therefore, whether urbanization saves land for nature.

The most populated clusters of cities are mainly located along the coastal zones and major waterways—in India, East Asia, on the eastern U.S. coast, and in western Europe (Figure 2). The cities experiencing the most rapid change in urban population between 1990 and 2000 are mostly located in developing countries (48) (Figure 2). It is estimated that 1 to 2 million ha of cropland are being taken out of production every year in developing countries to meet the land demand for housing, industry, infrastructure, and recreation (39). This is likely to take place mostly on prime agricultural land located in coastal plains and in river valleys. Note that rural households may consume more land per capita for residential purposes than their urban counterparts (39).

The Still Unmeasured Land-Cover Changes

Other forms of rapid land-cover change that are thought to be widespread are still poorly documented at the global scale. Local- to national-scale studies, however, demonstrate their importance and ecological significance. Prominent among these are changes in the (sub)tropical dry forests (e.g., Miombo forests in southern Africa and Chaco forests in South America); forest-cover changes caused by selective logging, fires, and insect damage; drainage or other forms of alteration of wetlands; soil degradation in croplands; changes in the extent and productive capacity of pastoral lands; and dryland degradation, also referred to as desertification, which remains a controversial issue.

THE COMPLEX NATURE OF LAND-COVER CHANGES

Conversion Versus Modification in Land Cover

The land cover is defined by the attributes of the earth's land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human structures. Data sets used in land-use/cover change research represent the land surface by a set of spatial units, each associated with attributes. These attributes are either a single land-cover category (i.e., leading to a discrete representation of land cover) (49) or a set of values for continuous biophysical variables (i.e., leading to a continuous representation of land cover) (50). The discrete representation of land cover has the advantages of concision and clarity, but it has led to an overemphasis of land-cover conversions and a neglect of land-cover modifications. *Land-cover conversions* (i.e., the complete replacement of one cover type by another) are measured by a shift from one land-cover category to another, as is the case in agricultural expansion, deforestation, or change in urban extent. *Land-cover modifications* are more subtle changes that affect the character of the land cover without changing its overall classification.

Recently, there has been increased recognition of the importance of the processes of modification of land attributes. For example, mostly *agricultural intensification*—defined as higher levels of inputs and increased output of cultivated or reared products per unit area and time—permitted an increase in the world's food production over the last decades (40). Thanks to the use of high-yielding crop varieties, fertilization, irrigation, and pesticides on land already under agriculture, crop yield increases have outpaced global human population growth (51). In the Brazilian Amazon, every year forest impoverishment caused by selective logging and fires affects an area at least as large as the area affected by forest-cover conversion (52). The expansion of woody shrubs in the western United States grasslands, following fire suppression and overgrazing, contributed to a large carbon sink (14, 53). The severity of soil erosion and its impact on associated resources in the United States has been debated because of discrepancies between estimates based on models and observed sediment budgets (8). Declines in tree density and species richness in the last half of the twentieth century were measured in a region of Senegal, in the West African Sahel, and provided evidence of desertification in that region (54). Another study in western Sudan, a region that was allegedly affected by desertification, did not find any decline in the abundance of trees despite several decades of droughts (55).

The monitoring of land-cover conversion can be performed by a simple comparison of successive land-cover maps. By contrast, the detection of subtle changes within land-cover classes—that is modifications—requires a representation of land cover where the surface attributes vary continuously in space and time, at the seasonal and interannual scales (50, 56). This representation allows detection of, for example, changes in tree density, in net primary productivity, or in the length of the growing season. Earth observation from satellite sensors provides repetitive and spatially explicit measurements of biophysical surface attributes, such as vegetation cover, biomass, vegetation community structure, surface moisture, superficial soil organic matter content, and landscape heterogeneity.

Analyses of multiyear time series of these attributes, their fine-scale spatial pattern, and their seasonal evolution have led to a broader view of land-cover change. Remote sensing data highlight high temporal frequency land-cover modifications of great importance for earth system processes. In particular, data from wide-field-of-view satellite sensors reveal patterns of seasonal and interannual variations in land surface attributes that are driven not by land-use change but rather by climatic variability. These variations include the impact on vegetation and surface moisture of the El Niño Southern Oscillation (ENSO) phenomena (57–59), natural disasters such as floods and droughts (60, 61), changes in the length of the growing season in boreal regions (62), and changes in vegetation productivity due to erratic rainfall fluctuations in the African Sahel, which lead to an expansion and contraction of the Sahara (63).

A study linking coarse resolution remote sensing data with rainfall data tested whether there was a decadal trend in the rain-use efficiency of the African Sahel region. It revealed the absence of widespread subcontinental-scale dryland degradation, although some areas did show signs of degradation (64). These results suggested that the resilience of the Sahel in primary production per unit rainfall has not changed despite serious droughts in the 1970s and 1980s. The impact of fires on land cover has also been well documented with remote sensing data (65), both for the mostly anthropogenic fires in tropical regions (66) and the mostly natural fires in boreal regions (67). Fires result from a combination of climatic factors, which determine fuel availability, fuel flammability, and ignition by lightning, and factors related to land-use/cover change that control fire propagation in the landscape and human ignition.

A combination of coarse and fine spatial resolution satellite sensors allowed measuring at the global scale land-cover changes caused by land-use change, such as deforestation in the humid tropics (30, 31) and change in nighttime city lights, which is a proxy for changes in urban extent and electrification (47). Although numerous local scale studies have mapped and quantified land-cover change with fine resolution remote sensing data, and there are a few subnational- to national-scale studies (35), there are remarkably few such studies at the regional to global scales. National-scale forest inventory and agricultural census data have also been analyzed, in some cases with remote sensing data, to refine estimates of rates and geographic patterns of change in forest cover and cropland (11, 14). Overall, the quantification of areas of rapid land-cover change still suffers from large uncertainties (36).

Progressive Versus Episodic Land-Cover Changes

Time series of remote sensing data reveal that land-cover changes do not always occur in a progressive and gradual way, but they may show periods of rapid and abrupt change followed either by a quick recovery of ecosystems or by a nonequilibrium trajectory. Such short-term changes, often caused by the interaction of climatic and land-use factors, have an important impact on ecosystem processes. For example, droughts in the African Sahel and their effects on vegetation are reinforced at the decadal timescale through a feedback mechanism that involves land surface changes caused by the initial decrease in rainfall (68). Grazing and conversion of semiarid grasslands to row-crop agriculture are the source of another positive desertification feedback by increasing heterogeneity of soil resources in space and time (69). The role of the Amazonian forest as a carbon sink (in natural forests) and source (from land-use changes and fires) varies from year to year as a result of interactive effects between deforestation, abandonment of agricultural land reverting to forests, fires, and interannual climatic variability (70, 71). In Indonesia, periodic El Niño-driven droughts lead to an increase in the forest's susceptibility to fires. Accidental fires are more likely under these conditions and lead to the devastation of large tracts of forests (72) and to the release of huge amounts of carbon from peatland fires (73). Large landholders also seize the opportunity of drought conditions to burn large tracts of forest to convert them to plantations. Forests that have been affected by forest fragmentation, selective logging, or a first fire subsequently become even more vulnerable to fires as these factors interact synergistically with drought (72, 74).

In summary, both land-cover modifications and rapid land-cover changes need to be better taken into account in land-cover change studies. Climate-driven land-cover modifications do interact with land-use changes. Slow and localized land-cover conversion takes place against a background of high temporal frequency regional-scale fluctuations in land-cover conditions caused by climatic variability, and it is often linked through positive feedback with land-cover modifications. These multiple spatial and temporal scales of change, with interactions between climate-driven and anthropogenic changes, are a significant source of complexity in the assessment of land-cover changes. It is not surprising that the land-cover changes for which the best data exist—deforestation, changes in the extent of cultivated lands, and urbanization—are processes of conversion that are not strongly affected by interannual climatic variability. By contrast, few quantitative data exist at the global scale for processes of land-cover modification that are heavily influenced by interannual climatic fluctuations, e.g., desertification, forest degradation and rangeland modifications.

EMPIRICAL EVIDENCE ON THE CAUSES OF LAND-USE CHANGE

Proximate Versus Underlying Causes

Land use is defined by the purposes for which humans exploit the land cover. There is high variability in time and space in biophysical environments, socio-economic activities, and cultural contexts that are associated with land-use change. Identifying the causes of land-use change requires an understanding of how people make land-use decisions and how various factors interact in specific contexts to influence decision making on land use. Decision making is influenced by factors at the local, regional, or global scale. Proximate (or direct) causes of land-use change constitute human activities or immediate actions that originate from intended land use and directly affect land cover (75). They involve a physical action on land cover. Underlying (or indirect or root) causes are fundamental forces that underpin the more proximate causes of land-cover change. They operate more diffusely (i.e., from a distance), often by altering one or more proximate causes (76). Underlying causes are formed by a complex of social, political, economic, demographic, technological, cultural, and biophysical variables that constitute initial conditions in the human-environment relations and are structural (or systemic) in nature (33, 77, 78).

Proximate causes generally operate at the local level (individual farms, households, or communities). By contrast, underlying causes may originate from the regional (districts, provinces, or country) or even global levels, with complex interplays between levels of organization. Underlying causes are often exogenous to the local communities managing land and are thus uncontrollable by these communities. Only some local-scale factors are endogenous to decision makers. An important system property associated with changes in land use is feedback that can either accentuate or amplify the speed, intensity, or mode of land change, or constitute human mitigating forces, for example via institutional actions that dampen, impede, or counteract factors or their impacts. Examples are the direct regulation of access to land resources, market adjustments, or informal social regulations (e.g., shared norms and values that give rise to shared land management practices).

Place-based research followed by systematic comparative analyses of case studies of land-use dynamics have helped to improve understanding of the causes of land-use change (10, 33, 79–83). These syntheses produced general insights on sectoral causes of land-use change and on the mode of interaction between various causes. They identified dominant pathways—also referred to as spirals, trajectories, or syndromes—leading to specific types of change. What has been lacking so far is the development of an integrative framework that would provide a unifying theory for these insights and pathways of land-use change and a more process-oriented understanding of how multiple macrostructural variables interact to affect micro agency with respect to land.

General Insights on Sectoral Causes of Land-Use Change

MULTIPLE CAUSES Land-use change is always caused by multiple interacting factors originating from different levels of organization of the coupled human-environment systems. The mix of driving forces of land-use change varies in time and space, according to specific human-environment conditions. Driving forces can be slow variables, with long turnover times, which determine the boundaries of sustainability and collectively govern the land use trajectory (such as the spread of salinity in irrigation schemes or declining infant mortality), or fast variables, with short turnover times (such as food aid or climatic variability associated with El Niño oscillation). Biophysical drivers may be as important as human drivers. The former define the natural capacity or predisposing conditions for land-use changes. The set of abiotic and biotic factors that determine this natural capacity varies among localities and regions. Trigger events, whether these are biophysical (a drought or hurricane) or socioeconomic (a war or economic crisis), also drive land-use changes. Changes are generally driven by a combination of factors that work gradually and factors that happen intermittently (82).

NATURAL VARIABILITY Natural environmental change and variability interact with human causes of land-use change. Highly variable ecosystem conditions driven by climatic variations amplify the pressures arising from high demands on land resources, especially under dry to sub-humid climatic conditions. Natural and socioeconomic changes may operate as synchronous but independent events. In the Iberian Peninsula during the sixteenth and seventeenth centuries, the peak of the Little Ice Age occurred almost simultaneously with large-scale clearing for cultivated land following the consolidation of Christian rule over the region. This cultivation triggered changes in surface hydrology and significant soil erosion (84). Natural variability may also lead to socioeconomic unsustainability, for example when unusually wet conditions alter the perception of drought risks and generate overstocking on rangelands. When drier conditions return, the livestock management practices are ill adapted and cause land degradation. This overstocking happened several times in Australia and, in the 1970s, in the African Sahel (84). Land-use change, such as cropland expansion in drylands, may also increase the vulnerability of human-environment systems to climatic fluctuations and thereby trigger land degradation.

ECONOMIC AND TECHNOLOGICAL FACTORS Available case studies highlight that, at the timescale of a couple of decades or less, land-use changes mostly result from individual and social responses to changing economic conditions, which are mediated by institutional factors. Opportunities and constraints for new land uses are created by markets and policies and are increasingly influenced by global factors (82, 85). Economic factors and policies define a range of variables that have a direct impact on the decision making by land managers, e.g., input and output prices, taxes, subsidies, production and transportation costs, capital flows and investments, credit access, trade, and technology (86). Internal consumption affects land less than external demand, so subsistence croplands consequently decrease while land under crops for markets increases with a parallel increase in agricultural intensity (87). Market access is largely conditioned by state investments in transportation infrastructure. The unequal distribution of wealth between households, countries, and regions determines geographic differences in economic opportunities and constraints. It affects, for example, who is able to develop, use, and profit from new technologies that increase efficiency in land management.

Improving agricultural technology—as much as providing secure land tenure and giving farmers better access to credit and markets—can potentially encourage more deforestation rather than relieving pressure on the forests (88). The differing impact of agricultural development on forest conversion depends on how the new technologies affect the labor market and migration, whether the crops are sold locally or globally, how profitable farming is at the forest frontier, as well as on the capital and labor intensity of the new technologies (88).

DEMOGRAPHIC FACTORS At longer timescales, both increases and decreases of a given population also have a large impact on land use. Demographic change does not only imply the shift from high to low rates of fertility and mortality (as suggested by the demographic transition), but it is also associated with the development of households and features of their life cycle. The family or life-cycle features relate mainly to labor availability at the level of households, which is linked to migration, urbanization, and the breakdown of extended families into several nuclear families. As an example of the latter phenomenon, the splintering of family herds in the West African Sudan-Sahel zone over the past 25 years—due to increases in nuclear households and the transfer of livestock wealth from herding families to merchants, agriculturalists, and government officials—led to increased investment in crop production, reduced labor availability among pastoral households, lower energy and skills applied to livestock husbandry, and reduced livestock mobility, which increased the risk of land degradation (89). Fuelwood demand by households in Africa differs between nuclear family units and larger consuming units; the latter are generally more energy efficient. Small consuming units thus cause more forest degradation, especially in peri-urban environments (90).

The internal dynamics of traditional and colonist families in humid forest frontiers in South America, which are mainly related to households' capital and labor constraints, explain the microlevel dynamics of land-cover modification by forest types (91), land quality (92), and gender division, as well as the changing social context of deforestation in the Amazon Basin (93–95). Forest clearing is caused by a variety of actors, with differing effects: recent in-migrants practice slash-and-burn agriculture; their children's families shift to fallow agriculture; long-settled families have diversified production; small families have crop/livestock combinations (associated with high rates of forest losses); large families have perennial production modes (associated with low rates of forest losses); and small ranchers are displaced by large ranchers, and upland croppers are displaced by lowland ranchers (96–99).

Life-cycle features arise from and affect rural as well as urban environments. They result from households' strategic responses to both economic opportunities (for example, market signals indicating higher crop profitability) and constraints (due to economic crisis conditions, for example). They shape the trajectory of land-use change, which itself affects the household's economic status (100, 101). Therefore, a population analysis of great nuances is required.

Migration in its various forms is the most important demographic factor causing land-use change at timescales of a couple of decades (33, 102). Migration operates as a significant driver with other nondemographic factors, such as government policies, changes in consumption patterns, economic integration, and globalization (87). Some policies resulting in land-use change either provoke (87) or are intricately linked with (103) increased migration.

The growth of urban aspirations, the urban-rural population distribution, and the impact of rapidly growing cities on ecosystem goods and services are likely to become dominant factors in land-use change in the decades to come, be it in major urban or peri-urban areas (87) or in remote hinterland or watershed areas (96, 104–106). Many new urban dwellers in developing countries still own rural landholdings (107). Although the growth of urban areas creates new local and regional markets for livestock, timber, and agricultural products, it also increases urban remittances to the countryside (82).

INSTITUTIONAL FACTORS To explain land-use changes, it is also important to understand institutions (political, legal, economic, and traditional) and their interactions with individual decision making (85, 108). Access to land, labor, capital, technology, and information is structured (and is frequently constrained) by local and national policies and institutions (109). Land managers have varying capabilities to participate in and to define these institutions. Relevant nonmarket institutions include: property-rights regimes; environmental policies; decision making systems on resource management (e.g., decentralization, democratization, and the role of the public, of civil society, and of local communities in decision making); information systems related to environmental indicators as they determine perception of changes in ecosystems; social networks representing specific interests related to resource management; conflict resolution systems concerning access to resources; and institutions that govern the distribution of resources and thus control economic differentiation.

There is often a mismatch between environmental signals reaching local populations and the macrolevel institutions (87, 110). Therefore, the rules used for making policies are important to ensure that local users are able to influence resource-management institutions (111). Institutions need to be considered at various scales, to identify the local mediating factors and adaptive strategies and to understand their interactions with national- and international-level institutions.

Many land-use changes are due to ill-defined policies and weak institutional enforcement, as exemplified by the widespread illegal logging in Indonesia linked to corruption and to the devolving of forest management responsibilities to the district level (112). On the other hand, recovery or restoration of land is also possible with appropriate land-use policies. Consolidation of landholdings and the shift from communal, traditional systems to formal, state-sanctioned regimes is a trend observed throughout the developing world (83). Examples of policies that influence land-use change are state policies to attain self-sufficiency in food (113); taxation, fiscal incentives, subsidies, and credits (93, 97, 114–116); price controls on agricultural inputs and outputs (87, 116); decentralization (113, 117); infrastructure support (87); (low) investments in monitoring and formally guarding natural resources (85); resource commodification (87, 116, 118, 119); land consolidation (120, 121), nationalization, and collectivization (87, 113); structural adjustment measures (101, 106, 122); and international environmental agreements.

With increasingly interconnected market forces and the rise of international environmental conventions, the impact of institutional drivers moves from the local to the global level. Land degradation is more prominent when macropolicies, either capitalist or socialist, undermine local adaptation strategies. In particular, perverse subsidies for road construction, agricultural production, forestry, and so forth are thought to be one of the biggest impediments to environmental sustainability (123).

CULTURAL FACTORS Numerous cultural factors also influence decision making on land use. Land managers have various motivations, collective memories, and personal histories. Their attitudes, values, beliefs, and individual perceptions influence land-use decisions—for instance through their perception of and attitude toward risk. Land-use decisions have intended and unintended consequences on ecosystems; these depend on the knowledge, information, and management skills available to land managers. Culture is often linked with political and economic inequalities, e.g., the status of women or ethnic minorities (76, 87), that affect resource access and land use. Understanding the controlling models of various actors may thus explain the management of resources, adaptive strategies, compliance or resistance to policies, or social learning and therefore social resilience in the face of land-use change.

GLOBALIZATION Researchers have recently argued that cross-cutting the local and national pathways of land-use/cover change are the many processes of globalization that amplify or attenuate the driving forces by removing regional barriers, weakening national connections, and increasing the interdependency among people and between nations. Globalization as such is not a driver of land-use change but is a process that underlies the other driving forces discussed above. Globalization accelerates or buffers the impact of these drivers on land use. For example, Barbier (124) identified land-use change as the immediate and principal environmental impact of economic liberalization and globalization—mostly trade liberalization and reforms to open up the agro-industrial sector—in Ghana and Mexico. Directly, increased agricultural productivity triggered forest conversion and increased land degradation from unsustainable production methods. Indirectly, agro-industrial development displaced the landless and rural poor, who were then pushed to marginal agricultural lands or to the forest frontier. Although the environmental effects of macroeconomic policies and trade liberalization are particularly important in countries with fragile ecosystems (e.g., semiarid lands and mangrove forests), international trade and other forms of globalization can also improve environmental conditions through green certification and eco labeling, wider and more rapid spread of technologies, better media coverage allowing international pressure on states that degrade their resources, and free circulation of people, which provides better educational and employment opportunities. Naylor et al. (125) showed, for example, that in a small island of Micronesia, international migration, foreign aid, and monetary remittances from family members living overseas have relieved the pressures of economic crowding on mangrove forests, despite an increase in population and a decline in local government jobs.

International institutions (including organizations within the U. N. system and nongovernmental organizations) can be instrumental in promoting and funding policies aimed at combating environmental degradation, setting political agendas, building consensus, and creating constraints and incentives for sustainable land management (126).

A Finite Set of Pathways of Land-Use Change

The various sectoral drivers of land-use change discussed above are strongly linked within and between levels of organization of human-environment systems. They interact directly, are linked via feedback, and thus often have synergetic effects. Any land manager also constantly makes trade-offs between different land-use opportunities and constraints associated with a variety of external factors. Moreover, various human-environment conditions react to and reshape the impacts of drivers differently, which leads to specific pathways of land-use change (82). The complexity in the combinations of causes giving rise to land-use change can be greatly reduced by recognizing that there are a limited number of ways in which these causes interact. In other words, a limited suite of processes and variables at any scale makes the problem tractable (127). The critical challenge is thus to identify dominant pathways and associated causes of land-use change. The risk factors associated with each pathway can then be identified.

Certain conditions appear repeatedly in case studies. They include but are not restricted to: loss of land productivity on sensitive areas following inappropriate use or the failure to maintain protective works (128, 129); development of the forest frontiers by weak state economies, for geopolitical reasons or to promote interest groups (94, 104); institutions in transition from communal to private land ownership in developing regions (93, 130); loss of entitlements to environmental resources (e.g., expropriation for large-scale agriculture, large dams, forestry projects, tourism, and wildlife conservation), that lead to an ecological marginalization of the poor (80, 131, 132); decrease in land availability due to encroachment by other land uses, such as land zoning for forest reserves, wilderness areas or agro-industrial plantations, which leads to the so-called tragedy of enclosure (96, 133); induced innovation and intensification (87, 134, 135), especially in peri-urban and market-accessible areas of developing regions (136); urbanization followed by changes in consumption patterns and in income distribution with differential rural impacts (87, 96, 120); new economic opportunities linked to new market outlets, changes in economic policies, or capital investments (114, 130, 137–139); breakdown of extended families with impacts on resource use efficiency (89, 90); inappropriate policy intervention giving rise to rapid modifications of landscapes and ecosystems (103, 140, 141); macroeconomic shocks and structural adjustment policies with undesirable consequences on natural resources (101, 106, 122, 142); lack of community's ability to cope with a deteriorating environmental situation, combined with absence of political will to mitigate damage and to alter the trajectory of change, which leads to delayed and ineffective social responses (10).

Case studies show that not all causes of land-use change and all levels of organization are equally important. For any given human-environment system, a limited number of causes are essential to predict the general trend in land use (127). This is the basis, for example, for the syndrome approach, which describes archetypical, dynamic, coevolutionary patterns of human-environment interactions (81). A taxonomy of syndromes links processes of degradation to both changes over time and status of state variables. The approach is applied at the intermediate functional scales that reflect processes taking place from the household level up to the international level. For example, the *overexploitation syndrome* represents the natural and social processes governing the extraction of biological resources through unsustainable industrial logging activities or other forms of resource use. Policy failure is one of the essential underlying driving forces of this syndrome (e.g., corruption, lobbyism, and weak or no law enforcement) (81). The typology of syndromes reflects expert opinion based on local case examples. The syndrome approach aims at a high level of generality in the description of mechanisms of environmental degradation.

Another approach, which has provided a classification of the situations in which environmental degradation occurs, is the study of regions at risk and environmental criticality by Kasperson et al. (10). Several case studies of regions under environmental degradation were described qualitatively by their histories. These qualitative trajectories were represented in terms of development of the wealth of the inhabitants and the state of the environment. A *critical environment* was defined as one in which the extent or the rate of environmental degradation precludes the maintenance of current resource-use systems or levels of human well-being, given feasible adaptations and the community's ability to mount a response (10). Different typical time courses of these variables were identified and interpreted with respect to more or less problematic future development of the regions. The Aral Sea, for example, was unquestionably a critical region after a few decades of Soviet-sponsored, ill-conceived large-scale irrigation schemes. Subsuming a particular case (e.g., the present situation and the history in a specified region) under one of these classes should allow for a restricted prognosis of its possible future development, which is a prerequisite for mitigation or adaptation.

Generic principles leading to environmental degradation can also emerge from careful comparison of diverse case studies. Kates & Haarmann (80) found a set of common interactive processes linking poverty and environmental degradation. Case studies told common tales of poor people's displacement from their lands, the division of their resources, and the degradation of their environments, which culminated in three major spirals of household impoverishment and environmental degradation driven by combinations of development and commercialization, population growth, poverty, and natural hazards. Lambin et al. (82) similarly identified typical pathways leading to tropical deforestation, agricultural intensification, rangeland modifications, and urbanization.

In summary, despite the large diversity of causes and situations leading to land-use change, there are some generalizable patterns of change that result from recurrent interactions between driving forces, following specific sequences of events. Even though, at the detailed level, these sequences may play out differently in specific situations, their identification may confer some predictive power by analogy with similar pathways in comparable regional and historical contexts.

A SYNTHESIS OF THE CAUSES OF LAND-USE CHANGE AND THEIR INTERACTIONS

The Five Fundamental High-Level Causes of Land-Use Change

Summarizing a large number of case studies, we find that land-use change is driven by a combination of the following fundamental high-level causes (Table 4):

TABLE 4 Typology of the causes of land-use change

	Resource scarcity causing pressure of production on resources	**Changing opportunities created by markets**	**Outside policy intervention**	**Loss of adaptive capacity and increased vulnerability**	**Changes in social organization, in resource access, and in attitudes**
Slow	Natural population growth and division of land parcels Domestic life cycles that lead to changes in labor availability Loss of land productivity on sensitive areas following excessive or inappropriate use Failure to restore or to maintain protective works of environmental resources Heavy surplus extraction away from the land manager	Increase in commercialization and agro-industrialization Improvement in accessibility through road construction Changes in market prices for inputs or outputs (e.g., erosion of prices of primary production, unfavorable global or urban-rural terms of trade) Off-farm wages and employment opportunities	Economic development programs Perverse subsidies, policy-induced price distortions and fiscal incentives Frontier development (e.g., for geopolitical reasons or to promote interest groups) Poor governance and corruption Insecurity in land tenure	Impoverishment (e.g., creeping household debts, no access to credit, lack of alternative income sources, and weak buffering capacity) Breakdown of informal social security networks Dependence on external resources or on assistance Social discrimination (ethnic minorities, women, members of lower classes or castes)	Changes in institutions governing access to resources by different land managers (e.g., shift from communal to private rights, tenure, holdings, and titles) Growth of urban aspirations Breakdown of extended family Growth of individualism and materialism Lack of public education and poor information flow on the environment
Fast	Spontaneous migration, forced population displacement, refugees Decrease in land availability due to encroachment by other land uses (e.g., natural reserves)	Capital investments Changes in national or global macro-economic and trade conditions that lead to changes in prices (e.g., surge in energy prices or global financial crisis) New technologies for intensification of resource use	Rapid policy changes (e.g., devaluation) Government instability War	Internal conflicts Illness (e.g., HIV) Risks associated with natural hazards (e.g., leading to a crop failure, loss of resource, or loss of productive capacity)	Loss of entitlements to environmental resources (e.g., expropriation for large-scale agriculture, large dams, forestry projects, tourism and wildlife conservation), which leads to an ecological marginalization of the poor

1. resource scarcity leading to an increase in the pressure of production on resources,
2. changing opportunities created by markets,
3. outside policy intervention,
4. loss of adaptive capacity and increased vulnerability, and
5. changes in social organization, in resource access, and in attitudes.

Some of these fundamental causes are experienced as constraints. They force local land managers into degradation, innovation, or displacement pathways. The other causes are associated with the seizure of new opportunities by land managers who seek to realize their diverse aspirations.

Each of these high-level causes can apply as slow evolutionary processes that change incrementally at the timescale of decades or more, or as fast changes that are abrupt and occur as perturbations that affect human-environment systems suddenly (Table 4). Only a combination of several causes, with synergetic interactions, is likely to drive a region into a critical trajectory (84).

Some of the fundamental causes leading to land-use change are mostly endogenous, such as resource scarcity, increased vulnerability and changes in social organization, even though they may be influenced by exogenous factors as well. The other high-level causes, such as changing market opportunities and policy intervention, are mostly exogenous, even though the response of land managers to these external forces is strongly mediated by local factors.

Mode of Interactions Between Causes of Change

The representation of interactions between these various causes of land-use change may be based on different patterns: one cause may completely dominate the other causes, assuming that land use in a given locality is influenced by whatever factor exerts the greatest constraint; factors driving land-use change can be connected as causal chains, i.e., interconnected in such a way that one or several variables (underlying causes, mainly) drive one or several other variables (proximate causes, mainly); different factors can intervene in concomitant occurrence, i.e., independent but synchronous operation of individual factors leading to land change; they may also intervene in synergetic factor combinations, i.e., several mutually interacting variables driving land-use change and producing an enhanced or increased effect due to reciprocal action and feedbacks between causes.

In meta-analyses of case studies of tropical deforestation (33) and dryland degradation or desertification by the same authors, the proportion of cases in which dominant, single, or key factors operate at either the proximate or underlying level was low (ca. 10% of the cases), as was the case with pure causal chains (ca. 5% to 8%). Concomitant occurrence of causes was more widespread (ca. 25%). The most common type of interaction was synergetic factor combinations (in 70% to 90% of the case studies reviewed).

In short,

$$\text{Land use} = f(\text{pressures, opportunities, policies, vulnerability, and social organization});$$

with

$$\begin{aligned}
\text{pressures} &= f(\text{population of resource users, labor availability, quantity of resources, and sensitivity of resources});\\
\text{opportunities} &= f(\text{market prices, production costs, transportation costs, and technology});\\
\text{policies} &= f(\text{subsidies, taxes, property rights, infrastructure, and governance});\\
\text{vulnerability} &= f(\text{exposure to external perturbations, sensitivity, and coping capacity}); \text{ and}\\
\text{social organization} &= f(\text{resource access, income distribution, household features, and urban-rural interactions})
\end{aligned}$$

with the functions f having forms that account for strong interactions between causes of land-use change.

Feedback and Endogeneity

In most cases, the patterns of causation discussed above are simplifications that are useful for communicating about particular environmental issues or for modeling. In reality, there are functional interdependencies between all the causes of land-use change, both at each organizational level, "horizontal interplay," and between levels of organization, "vertical interplay" (143).

Even at short timescales, the direction of causality may be difficult to establish, as illustrated by the case of roads and deforestation. For example, 81% of the deforestation in the Brazilian Amazon between 1991 and 1994 occurred within 50 kilometers of four major road networks (144). Is it the national demand for land and the high agricultural suitability of some forest areas that lead to policy decisions to expand the road network in these areas, which then gives access to the forest for migrants who clear land? Or is it the expansion of local logging or agricultural activities in some forest areas that then justifies the construction of new roads to link these active production areas to existing markets? Or does the construction of a road for reasons unrelated to land use in the forest (e.g., to connect major cities) induce new deforestation by its mere presence, through a spatial redistribution of population and activities? Or, in the latter case, does the road simply attract to a given location a preexisting demand for land that would have led to deforestation elsewhere if the road had not been built? In other words, is a road an endogenous or exogenous factor in deforestation and does it affect just the location or also the quantity of deforestation in a given country? The likely answer to these questions is that, in most cases, national demand for land, policies to develop the forest frontier, capital investments in logging and agricultural activities, population movements, commodification of the economy, the development of urban markets, and infrastructure expansion are highly interdependent and coevolve in close interaction as part of a general transformation of society and of its interaction with its natural environment.

As the timescale of analysis expands, all causes of land-use change—from demographic changes to technological innovations, which include new environmental policies—become endogenous to the human-environment system and are affected in some degree by land-use change. Actually, the changes in ecosystem goods and services that result from land-use change lead to important feedback on the drivers of land-use change. Changes in ecosystems affect the availability and quality of some of the natural resources that are essential to sustain livelihood, create opportunities and constraints for new land uses, induce institutional changes at the local to global levels in response to perceived and anticipated resource degradation, modify the adaptive capacity of land managers (by affecting their health, for example), and give rise to social changes in the form of income differentiation (when there are winners and losers in environmental change) or increased social complexity (e.g., by increasing interactions between urban and rural systems).

Land-Use Change as an Emergent Property of Complex Adaptive Systems

Land use is never static, but it is constantly changing in response to dynamic interaction between drivers and feedback from land-use change to these drivers. In other words, human-environmental systems are complex adaptive systems in which properties, such as land use, emerge from the interactions among the various components of the entire system, which themselves feed back to influence the subsequent development of those interactions (127). Land-use change is a spatial property observed at the scale of a landscape. It is the sum of many small, local-scale changes in land allocation that reinforce or cancel each other. These changes are the product of multiple decisions resulting from interactions between diverse agents, who act under certain conditions, anticipate future outcomes of their decisions, and adapt their behaviors to changes in external (e.g., the market) and internal (e.g., their aspirations) conditions. In most cases, these decisions are made without central direction, unless there are central planning systems. Land-use change is thus a complex large-scale spatial behavior that emerges from the aggregate interactions of less complex agents. Human-environment systems associated with land use have similar attributes and are governed by mechanisms and processes similar to those of other complex adaptive social or biological systems (145–147).

The exact future of the behavior of coupled human-environment systems is often unpredictable because it is emergent rather than predetermined. Hence, there is an interest in place-based research as a method to reveal a large repertoire of pathways of land-use change, in a range of human-environment conditions.

Land-Use Transitions

Land-use change is associated with other societal and biophysical changes through a series of transitions (148). A transition can be defined as a process of societal change in which the structural character of society (or a complex subsystem of society) transforms (149). It results from a set of connected changes, which reinforce each other but take place in several different components of the system. Multiple causality and coevolution of different sectors of society caused by interacting developments are central to the concept of transition. Transitions in land use must be viewed as multiple and reversible dynamics. A transition is not a fixed pattern, nor is it deterministic. It is not set in advance, and there is large variability in specific trajectories. There is thus a strong notion of instability and indeterminacy in land-use transitions. Transitions should be viewed as "possible development paths where the direction, size, and speed can be influenced through policy and specific circumstances" (149).

The concept of transition has been applied in land-use change studies at different spatial and temporal scales. A forest transition has been described at a national scale to represent the change from decreasing to expanding national forest areas that has taken place over a century or more in several European countries and in North America, by afforestation and natural regeneration mostly on abandoned marginal agricultural land once societies began to industrialize and urbanize (150, 151). Forests in the Mediterranean basin did not make this transition. Some regions in the tropics currently show signs of significant reforestation. A predominantly national focus in forest transition studies (150–152) has been increasingly complemented by analyses at the subnational scale (153, 154). Case studies have also identified transition-like trajectories that suggest, over a decade or so, households undertake management of already cleared areas following a period of rapid deforestation, stop deforesting, and even undertake afforestation within their individual parcels (155–157).

INTEGRATIVE FRAMEWORKS TO UNDERSTAND LAND-USE/COVER CHANGES

How to overcome the somewhat futile observation that everything is interrelated? The level of integration in research on land-use/land-cover change requires a combination of perspectives of understanding: the agent-based, the systems, and the narrative approaches (19). Each perspective approaches the impact on land of the interactions between macrostructure and microagency from a different vantage point. These perspectives can be and are combined in various ways in integrated, place-based research on causes and impacts of land-use change; examples include the Yucatán (158), the Serengeti-Mara ecosystem (132), the Nang Rong District in northeastern Thailand (159, 160), the Ecuadorian Amazon (161), the Belgian Ardennes (162), the Yaqui valley in Mexico (163), the African Sahel

(164, 165), and other integrated land change studies over a particular geographical region. These perspectives still have to be integrated in the modeling of land-use change.

Agent-Based Perspective

The agent-based perspective is centered on the general nature and rules of land-use decision making by individuals. It represents the motivations behind decisions and the external factors that influence decisions about land use. It applies approaches that range from the rational decision making of neoclassical economics to household, gender, class, and other dimensions common to the social and behavioral sciences. Local ecosystem managers have many motives, some intentional and others unconscious, related to economic, traditional, emotional or biophysical factors (76). Economic models of land-use change, for example, assume that land managers attempt to fulfill their needs and meet their expectations by accommodating economic, social, and environmental constraints (utility optimization). Land managers evaluate expected outcomes of their land-use decisions. If undesired environmental impacts are foreseen, they modify factor allocation (22).

As an example of the agent-based perspective, authors have analyzed the diversity of responses by land managers to population growth. Whereas the emphasis of Boserup's work (166) is on technological responses, Bilsborrow (167) analyzed several demographic responses in the face of land shortage and declining yields. They are of two sorts: outmigration and fertility reduction through postponement of marriage or reduction in marital fertility. Bilsborrow & Ogendo (168) further describe local changes in tenure arrangements, which can be the first adaptations of land-use practices to population growth. They usually follow the sequence of distribution of idle land for agricultural use, reduction of landholding size in the community, creation of new categories of access rights, and reclassification of old ones to exclude nonpermanent members. Moreover, these tenurial, technological, and demographic responses can be multiphasic, i.e., occurring simultaneously—as conceptualized by Davis (169), rather than sequential. Their effects are thus difficult to separate.

Microeconomic approaches to land-use changes explain spatial configurations of changes. Any parcel of land, given its attributes and location, is assumed to be allocated to the use that earns the highest rent (170). This rent is a function of the returns and costs of land conversion, given supply and demand functions of the land market, which is assumed to be competitive (171). Deforestation, for example, is driven by choices by land managers among alternative rents (172, 173). Microeconomic approaches usually assume that the agents have the ability to make informed predictions and plans and that they are risk minimizers. After exploring all options available to them, individuals make rational decisions based on available information, obligations, and expectations (social as well as economic) to balance anticipated returns and risks.

Systems Perspective

The systems/structures perspective explains land-use change through the organization and institutions of society (174). Institutions, such as governments, communities, or markets, operate interactively at different spatial and temporal scales; the institutions link local conditions to global processes and vice versa. Although some institutions are direct drivers of change, others, such as markets, are intricately linked to individual decisions. The systems perspective represents the dynamics of economy-environment linkages operating at regional to global scales. It has to cope with issues that include technological innovations, policy and institutional changes, collective ownership of land resources, rural-urban dynamics, and macroeconomic transformations.

The systems perspective highlights, for example, how communities are trapped in a degradational pathway given complex mechanisms that may have their roots outside the area subjected to degradation. For instance, Blaikie & Brookfield (175), Leonard (131) and Kates & Haarman (80) discuss the process of marginalization of poor people in remote and ecologically fragile rural areas. This ecological marginalization usually follows population growth, agricultural modernization—associated with mechanization and land consolidation—inequalities in land tenure in the most fertile and accessible agricultural regions, or other pressures of social or political origin. It leads to migration of poor farmers into areas with a high ecological sensitivity for which existing management practices may be inadequate.

Narrative Perspective

The narrative perspective seeks depth of understanding through historical detail and interpretation (176, 177). It tells a land-use/cover change story for a specific locality (178–180). Historical analyses of landscape grasp all the complexity of events, in particular stochastic or nonrandom but unpredictable events that significantly affect land-use/land-cover changes. It includes changing political economies, environmental feedback on land use, and external shocks (181). The narrative perspective recognizes the path dependence of recent evolutions. It avoids the simplifications and erroneous interpretations that could result from studies focused only on the present and immediate past, outside the context of longer histories of human-environment interactions (109). For example, Fairhead & Leach's (182) historical study of contemporary forest islands in Guinea showed that these were human creations in a savanna landscape, where farmers have turned fallow vegetation more woody around their villages. These patches of dense forests in the savanna had long been regarded as the last relics of a once more extensive forest cover, degraded due to its inhabitants' land use. The narrative approach also allows distilling from changing human-environment conditions those dynamics crosscutting different eras or episodes of use and occupation and those unique to individual episodes (181).

Scenarios generated to project future land-use changes or to identify land-use patterns with certain optimality characteristics are based on narrative story lines to describe consistently the relationships between driving forces of environmental changes and their evolution (183). The scenarios are hypothetical sequences of events that provide alternative images of how the future might unfold. Scenarios consist of states, driving forces, events, consequences, and actions that are internally consistent and plausible (183). They provide insights into the present by drawing analogies between historical and current situations.

CONCLUSION AND FUTURE RESEARCH

Significant progress in the quantification and understanding of land-use/cover changes has been achieved over the last decade. Much remains to be learned, however, before we can fully assess and project the future role of land-use/cover change in the functioning of the earth system and identify conditions for sustainable land use. New estimates of areas and rates of major land-use/cover conversions have greatly narrowed down uncertainties. Sometimes initial estimates of the spatial importance of these changes have been revised downward. But often, the significance of land-use/cover change for earth system processes has been revised upward. A number of more subtle land changes still need to be better quantified at a global scale. This is particularly the case for anthropogenic changes that strongly interact with natural environmental variability and therefore require longitudinal data over a long time period for a reliable assessment.

Analyses of the causes of land-use change have moved from simplistic single-cause explanations to an understanding that integrates multiple causes and their complex interactions. A few general pathways leading to land-use change have been identified from a wealth of local case studies. This inductive process of generalization paves the way for the development of more realistic models of land-use change. Nevertheless, different perspectives of understanding still tend to follow different lines of explanation of the causes of land-use change because each focuses on specific organizational levels and temporal scales of the human-environment systems. Whereas a systems perspective tends to focus on gradual and progressive processes of change at the scale of large entities, the agent-based perspective deals with people's own foreseeable futures at the individual level, and the narrative perspective adopts a much longer time horizon and focuses on critical events and abrupt transitions. Different assumptions about temporality lead to varying explanations and interpretations of the causes and significance of environmental changes. These assumptions should be made explicit to facilitate the development of an integrative theory of human-environment relationships. We also argued in this paper that a systematic analysis of local scale land-use change studies, conducted over a range of timescales, helps to uncover general principles to provide an explanation and prediction of new land-use changes.

Improved understanding of the complex dynamic processes underlying land-use change will allow more reliable projections and more realistic scenarios of future changes. Crucial to projections is understanding factors that control positive and negative feedback in land-use change. Positive feedback loops amplify change and lead, in some cases, to a rapid degradation of ecosystems and the impoverishment of the societies using these ecosystems. By contrast, institutional and technological innovations may lead to negative feedback loops that decrease the rate of change or even reverse land-use/cover change trends. The relative strength of amplifying and attenuating feedback can be influenced by policies that control switches between land-use/cover change regimes dominated by positive or negative feedback. The analysis of interaction, coherence, or conflict between social and biophysical responses to changes in both ecosystem services and earth system processes caused by land changes is still a largely unresearched area. It will be a central focus of the new Land project of the IGBP and IHDP.

Improved understanding of processes of land-use change has led to a shift from a view condemning human impact on the environment as leading mostly to a deterioration of earth system processes to emphasis on the potential for ecological restoration through land management (184). This change reflects an evolution of the research questions, methods, and scientific paradigm.

First, initial concerns about global land-use/cover change arose from the realization that land transformation influences climate change and reduces biotic diversity, hence the interest in deforestation, desertification, and other changes in natural vegetation. The more recent focus on issues related to ecosystem goods and services, sustainability, and vulnerability has led to a greater emphasis on the dynamic coupling between human societies and their ecosystems at a local scale.

Second, research methods applied in land-use/cover change research were initially largely influenced by advances in remote sensing. This technology has led to an emphasis on short timescales, because earth observation data have been available only for a few decades. Recently, a wide range of other methods have been used to reconstruct long-term changes in landscapes. This change in temporal frame has led to a greater consideration of the long-term processes of ecological restoration and land-use transition.

Finally, whereas the notion of equilibrium used to dominate thinking about environmental change, a nonequilibrium paradigm, as well as concepts related to complex system dynamics, is now influencing land-use/cover change research. Rather than interpreting deviations from a predisturbance state as problematic, land-use changes are now increasingly analyzed as part of the system interactions leading to coevolution of natural and social systems. Throughout their history, human societies have coevolved with their environment through change, instability, and mutual adaptation. The coupled human-environment systems should therefore be considered as a whole when we assess sustainability and vulnerability.

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Figure 1 Main tropical deforestation fronts in the 1980s and 1990s. The map is based on three data sets: (a) the deforestation hotspots in the humid tropics of the Tropical Ecosystem Environment Observation by Satellite (TREES) project (34), (b) a time series analysis of tree cover based on 8-km resolution data from the National Oceanic and Atmospheric Administration's advanced very high resolution radiometer (AVHRR) (31), and (c) the Amazon Basin deforestation maps derived from time series of Landsat Thematic Mapper (Landsat TM) data (35). These maps were overlaid and combined to identify areas where high rates of deforestation were measured by several of the datasets. *Green* areas are intact forests. The map indicates the number of times each 0.1° grid was identified as being affected by rapid deforestation by the different datasets (*orange*, pixels detected as hotspot by one dataset, *red*, pixels detected as hotspot by two datasets, *black*, pixels detected as hotspot by three datasets) (36).

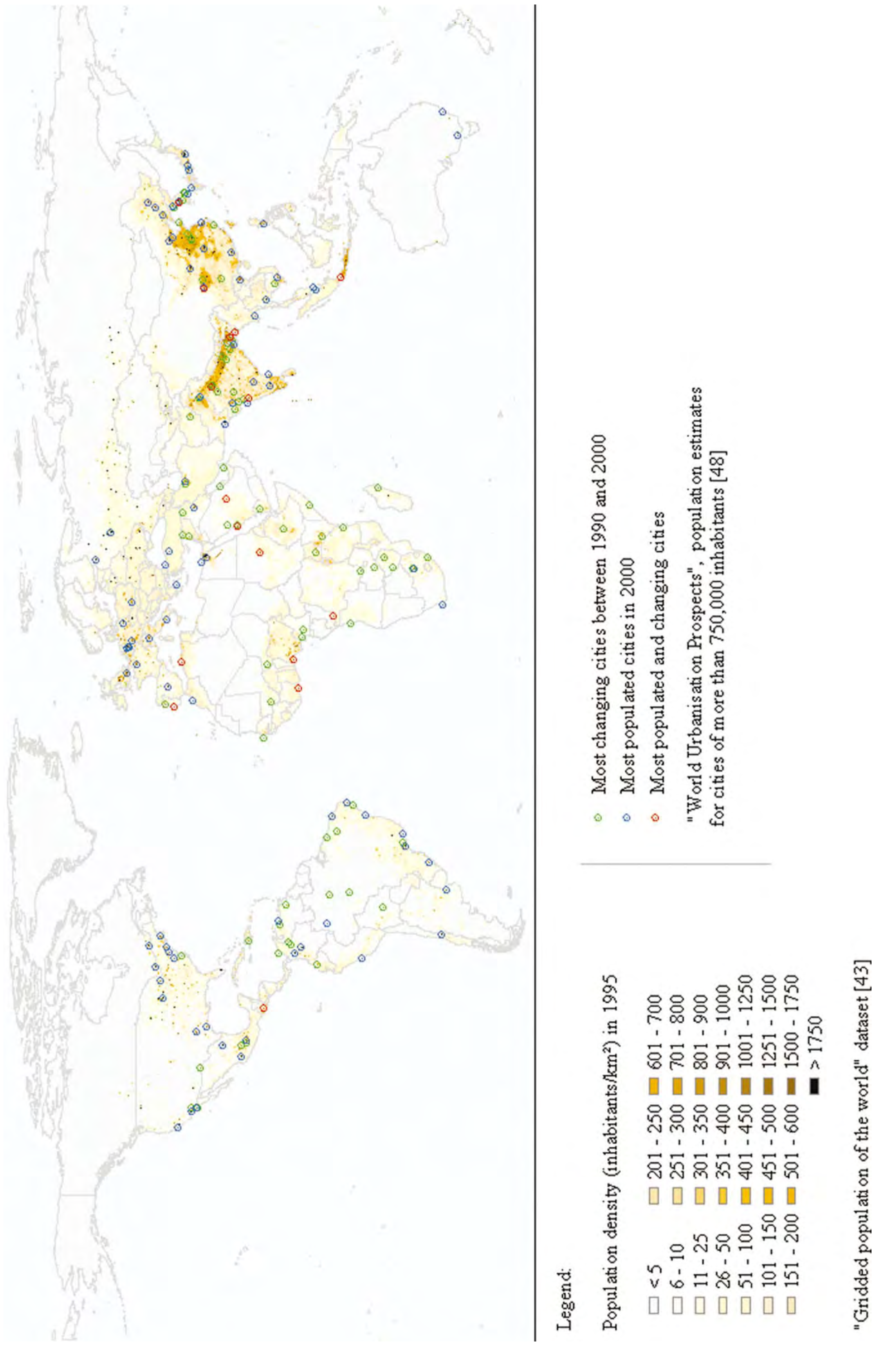

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Figure 2 Population density in 1995 and most populated and changing cities from 1990 to 2000. The map is based on the 2001 revision of the "World Urbanization Prospects" (43), which provides population estimates in cities of more than 750,000 inhabitants for the years 1990 and 2000, and the "gridded population of the world" (48), which provides population estimates in 1995. The first dataset focuses on megacities whereas the second includes less populated areas. *Green circles* represent the most changing cities between 1990 and 2000, *blue circles* the most populated cities in 2000, and *red circles* the most changing and populated cities. The background color scale represents the population densities in 1995 (from less than five inhabitants in *gray* to more than 1750 inhabitants/km^2 in *dark orange*) (36).

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DECLARATION OF BRUCE E. DALE, Ph.D.

EXHIBIT D

The Global Potential of Bioenergy on Abandoned Agriculture Lands

J. ELLIOTT CAMPBELL,*,†,‡ DAVID B. LOBELL,§ ROBERT C. GENOVA,† AND CHRISTOPHER B. FIELD†

Department of Global Ecology, Carnegie Institution of Washington, Stanford, California 94305, Department of Biological Sciences, Stanford University, Stanford, California 94305, and Program on Food Security and the Environment, Stanford University, Stanford, California 94305

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Converting forest lands into bioenergy agriculture could accelerate climate change by emitting carbon stored in forests, while converting food agriculture lands into bioenergy agriculture could threaten food security. Both problems are potentially avoided by using abandoned agriculture lands for bioenergy agriculture. Here we show the global potential for bioenergy on abandoned agriculture lands to be less than 8% of current primary energy demand, based on historical land use data, satellite-derived land cover data, and global ecosystem modeling. The estimated global area of abandoned agriculture is 385−472 million hectares, or 66−110% of the areas reported in previous preliminary assessments. The area-weighted mean production of above-ground biomass is 4.3 tons ha^{-1} y^{-1}, in contrast to estimates of up to 10 tons ha^{-1} y^{-1} in previous assessments. The energy content of potential biomass grown on 100% of abandoned agriculture lands is less than 10% of primary energy demand for most nations in North America, Europe, and Asia, but it represents many times the energy demand in some African nations where grasslands are relatively productive and current energy demand is low.

Introduction

Agricultural land dedicated to bioenergy crops is expanding rapidly (*1*), with multiple consequences for global climate, ecosystems, and food security (*2*). These consequences are closely tied to the land that is used for bioenergy crops. Using food agriculture lands for bioenergy agriculture could increase the cost of the food commodities that are critical to the diets of food-insecure people worldwide (*3–5*). Clearing forest land for new bioenergy crops could result in CO_2 emissions from terrestrial carbon pools that are much greater than any greenhouse gas benefits provided by biofuels (*6–11*). Raising bioenergy crops on agriculturally degraded and abandoned lands is emerging as a sustainable approach to bioenergy that provides environmental benefits and climate change mitigation without creating food−fuel competition for land or releasing the carbon stored in forests (*12, 13*). These lands have been defined as areas that have been abandoned to crop and pasture due to the relocation of agriculture and due to degradation from intensive use (*14, 15*). Growing conventional crops on these lands as a bioenergy feedstock could increase rates of erosion and polluted runoff (*16*), while field studies suggest that growing low-input, perennial grasses as a feedstock would likely reduce such impacts (*13, 17*).

Assessing the global potential of bioenergy production from agriculturally degraded and abandoned lands is challenging because of the high uncertainty associated with the spatial extent of these lands and the potential plant production on these lands. Existing assessments have provided only rough global estimates of the potential bioenergy from these lands, using estimates of the global area that are ultimately based on expert opinion (*18–20*), the assumption of a homogeneous spatial distribution, and spatially invariant or highly aggregated estimates of plant production. Such estimates range from 430 to 580 Mha of abandoned agriculture land, with mean global plant production on these lands of 1−10 tons aboveground biomass (AGB) ha^{-1} yr^{-1}, meeting 2−23% of current global primary energy demand (*13, 21, 22*). In previous work, we developed a new method for estimating the abandoned areas that relies on historical land use data and found that the potential biomass production has an energy content of ∼5% of primary energy demand (*23*). Application of our data-driven approach at the national level could help inform policy makers of the potential scale of this bioenergy resource (*24*).

Here we present a new global, spatially explicit estimate of abandoned agriculture and the associated plant production on these lands, using historical land use data, satellite-derived land cover, and global ecosystem modeling. We considered abandoned agriculture as land that was previously used for crop or pasture but has since been abandoned (and has not been converted to forest or urban areas). The spatially resolved biomass production is then combined with national-level energy use data to determine the potential contributions of bioenergy.

Methods

We estimated abandoned agriculture areas using the historical land use data from the History Database of the Global Environment 3.0 (HYDE, 5 min resolution) (*25, 26*). The HYDE gridded maps provide the fractional area of crop and the fractional area of pasture within each grid cell for each decade between 1700 and 2000. Abandoned areas were determined from each map grid cell that had decreasing agriculture areas over time. Shifting agriculture, which also contributes to abandoned agriculture lands (*15*), is not included in these maps. As a check on this HYDE-based analysis, we also considered areas of abandoned crop from the Center for Sustainability and the Global Environment (SAGE) land use database (5 min resolution) (*27, 28*).

While the HYDE database provides the fractional areas of both crop and pasture, it does not provide the underlying land use transitions (*15*). For example, if a grid cell shows a decrease in the fractional area of pasture and an increase in crop then it is not explicit whether these changes were due to a land use transition from pasture to crop or from pasture to some other land cover within the grid cell. Understanding this transition is important because transitions between pasture and crop should not be counted toward the area of abandoned agriculture. We used two alternative approaches to estimate these land use transitions that provide a low and high estimate of total abandoned agriculture for each grid cell. In the more restrictive approach, providing the low

* Corresponding author phone: (650) 462-1047; fax: (650) 462-5968; e-mail: campbell@stanford.edu.

† Department of Global Ecology, Carnegie Institution of Washington.

‡ Department of Biological Sciences, Stanford University.

§ Program on Food Security and the Environment, Stanford University.

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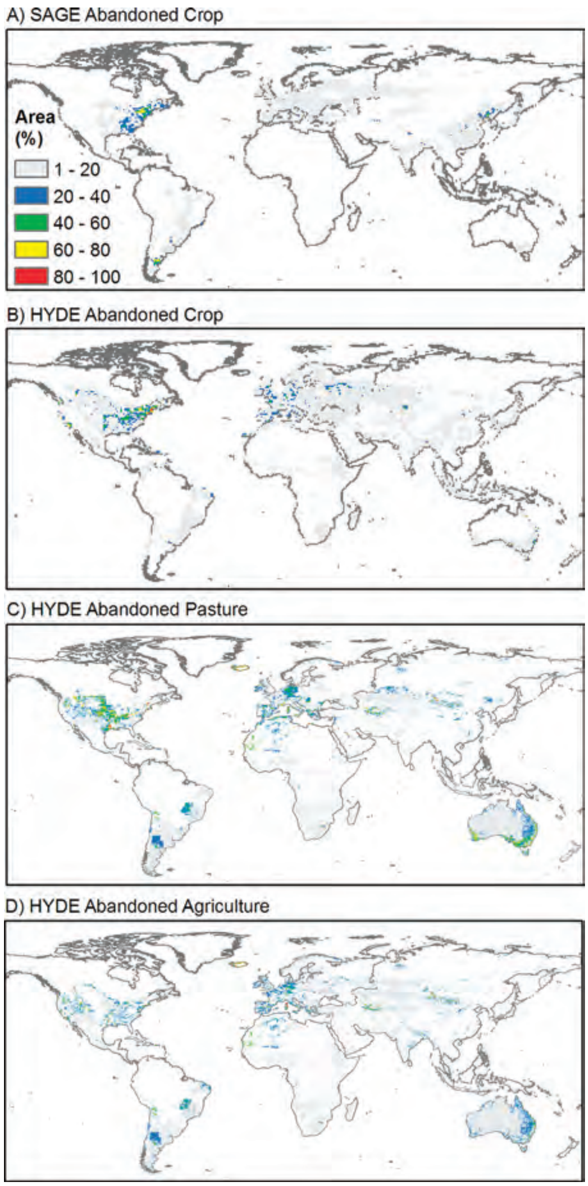

FIGURE 1. Global land areas of crop and pasture abandonment. (A and B) Crop lands that have been permanently converted to land uses other than cropping based on SAGE data andHYDE data. (C) Pasturelands that have been permanently converted to land uses other than pasture based on HYDE data. (D) Total abandoned agriculture based on HYDE data excluding areas resulting from land use transitions of crop to pasture, pasture to crop, agriculture to forest, and agriculture to urban (average of higher and lower estimate).

estimate, we considered any simultaneous increase in crop and decrease in pasture to be a transition from crop to pasture, and vice-versa. In the second approach, providing the high estimate, we calculated abandoned crop area for each grid cell as the difference between the maximum fractional crop area ever attained in a grid cell and the fractional crop area in the year 2000 (when this difference was positive). We followed the same approach for calculating abandoned pasture area. We then estimated the abandoned agriculture for each grid cell to be equal to the sum of the abandoned pasture and abandoned crop areas, but no greater than the difference of the total grid cell land area and the current agriculture area. This is a more self-consistent definition of land use transitions than in our earlier study (*23*), which used MODIS land cover to constrain the land use transitions between pasture and crop.

To exclude areas where abandoned agricultural lands have transitioned to forest or urban areas, we used a MODIS satellite map of the current forest and urban land cover (3 min resolution, MODIS/Terra Land Cover types MOD12C1) (*29*). Combining HYDE and MODIS data within this spatial analysis can introduce errors due to the different assumptions and input data used by the two data sets. Furthermore, the HYDE data provide subgrid cell information (fractional areas) while the MODIS data provide a single classification for the entire grid cell. We discuss the uncertainties in the following section. As a point of comparison, we also estimate the abandoned land area that has transitioned to forest or urban areas based on the International Geosphere Biosphere Programme (IGBP) DIScover data set (*30, 31*).

The biomass production at a specific location will depend on multiple factors including the crop type, management, climate, and soils. Natural production provides an upper estimate of potential agriculture production because agricultural harvest statistics, at a global scale, have been found to be about 65% of natural production (*32*). To provide an upper envelope estimate on the production potential, we used simulated natural plant production from the Carnegie-Ames-Stanford Approach (CASA) ecosystem model (1 degree resolution) (*33*). Estimating biomass yield with the natural production model on a site reflects local constraints from climate and soil types. The simulations (*33*) were driven by climate data (*34*), surface insolation (*35*), soil texture (*36*), land cover (*37*), and the normalized difference vegetation index (NDVI) (*33*). Using simulated natural production allows for the possibility that the total plant production from biomass agriculture may be significantly higher than that for current agriculture, at the global scale. The NDVI input may be sensitive to degradation which may decrease yields (*13*). We do not account for irrigation or very high fertilizer inputs, which could increase yields (*38–40*). Above-ground production rates may also overestimate harvestable biomass as some plant material must be left on the land to prevent further soil degradation (*41*).

Results and Discussion

Based on the HYDE historical land use data we found that between the years 1700 and 2000, 269 Mha of crop lands were permanently converted to land uses other than cropping (Figure 1B), while 479 Mha of pasture lands were converted to land uses other than pasture (Figure 1C), at some point in the last 300 years. This HYDE-based abandoned crop area is somewhat higher than the 210 Mha of abandoned crop area from the SAGE crop data (Figure 1A) (*28*). The abandoned crop areas from HYDE and SAGE data had the highest concentrations over the Eastern United States, as a result of the relocation of cropland from the Eastern to the Midwestern region of North America. The most extensive area of abandoned pasture was over the Midwestern region of North America, where HYDE data indicate that cropland has replaced pasture land. Australia, where pasture areas peaked in the mid-1970s and have since steadily declined, also had high levels of pasture abandonment in the data. We found that 99% of the land abandonment occurred during the past 100 years.

Our low and high approaches to estimating the global area of abandoned agriculture (crop and pasture) yield total areas of 474 and 579 Mha, respectively. These estimates exclude abandoned agriculture areas arising from the conversion of crop to pasture or pasture to crop. These estimates do not exclude abandoned areas arising from agriculture to forest or agriculture to urban transitions. Overlaying the MODIS land cover data, we identified the current land cover classification of each grid cell containing abandoned agriculture areas. Excluding pixels classified as forest or urban areas yielded estimates of 385 and 472 Mha for the low and high approaches, respectively (Figure 1D).

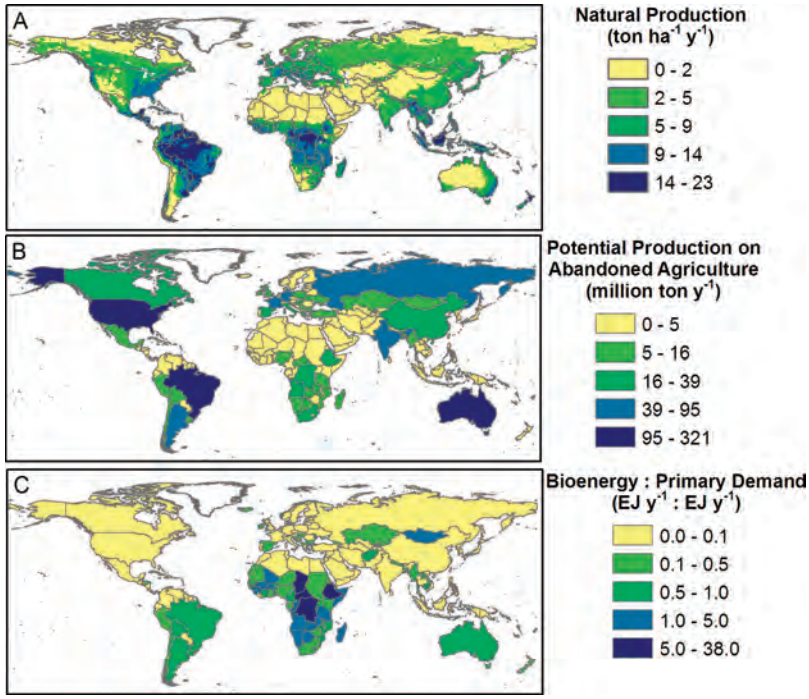

FIGURE 2. Biomass production potential on abandoned agriculture lands. (A) Natural above-ground production of biomass on all lands determined from the CASA model, assuming 50% of the biomass is above-ground and the ratio (by mass) of biomass to carbon is 2.2. (B) Potential above-ground production of biomass on abandoned agriculture lands at the country level. (C) Ratio of the energy content of the biomass on abandoned agriculture lands relative to the current primary energy demand at the country level. The energy content of biomass is assumed to be 20 kJ g^{-1}.

Our area estimates are 66−110% of the areas assumed in previous preliminary assessments (*13, 22, 42*). Excluding additional areas where abandoned agriculture has transitioned to other natural ecosystems types may also be important for maintaining species habitat and preserving natural carbon pools.

Our spatial analysis, relying on both HYDE and MODIS data, introduces additional uncertainty due to the different methods used in the creation of these data. Specifically, historical HYDE maps were, in part, spatially distributed by human population at the subadministrative level (*25, 26*). Since the subadministrative level distribution may be biased toward urban areas, our exclusion of MODIS urban areas may overcorrect our abandoned area estimate. However, the abandoned agriculture areas were reduced by only 3% when using the MODIS data to exclude urban areas. Our application of the MODIS forest map appears to have correctly excluded forest regrowth in the eastern United States (Figure 1D) where abandoned agriculture has transitioned to secondary forests (*43*). Alternatively, using the IBGP land cover data to exclude forest and urban areas resulted in a remaining abandoned agricultural area of 388−480 Mha. The IGBP area estimate is somewhat higher than the MODIS-based estimate of 385−472 Mha.

Using the global distribution of potential plant production (Figure 2A), we found that the abandoned agriculture lands could produce between 1.6 and 2.1 billion tons of AGB per year for the low and high area estimates, respectively. Potential production rates on abandoned lands are highest in regions of tropical grasslands, ranging from 7 to 20 tons AGB ha^{-1} y^{-1}. Globally, the area-weighted average of the production rates on abandoned lands was 4.3 tons AGB ha^{-1} y^{-1}. This is somewhat less than the global average of 4.9 tons AGB ha^{-1} y^{-1} extrapolated from plot experiments (*13*) and in the middle of the range of 1−10 tons AGB ha^{-1} y^{-1} assumed in a preliminary modeling study (*22*).

The energy content of 1.6−2.1 billion tons of dry biomass is 32−41 EJ or 7−8% of primary energy demand. We assumed a high value for energy content of 20 kJ g^{-1}, although this value will depend on multiple factors such as plant type and the timing of harvest (*44*). At the national scale, the bioenergy potential was largest in the United States, Brazil, and Australia, where the available areas were the most extensive (Figure 2B). The national bioenergy potential was less than 10% of primary energy demand for most countries in North America, Europe, and Asia while it represents many times the current energy demand in some African nations where grasslands are relatively productive and current fossil fuel demand is low (Figure 2C). Converting the bioenergy crops to liquid fuels would cut the net energy to half this amount and could result in either a net greenhouse gas source or sink depending on the types of agriculture and biorefineries used (*45–48*).

Overall, the potential bioenergy from abandoned agriculture lands is a small but meaningful fraction of global primary energy consumption. Regionally, it can be more important. The global potential could be increased with additional land areas or through fundamental advances in biomass agriculture. One possible source of additional lands is marginal agricultural lands that have limited potential for food production. Land areas degraded from wood harvesting (*49*), rather than agriculture, are another possible source of land. Forest lands could also produce net greenhouse gas sinks for highly productive sites under sustainable harvest practices (*50*). Consideration of these additional areas will require careful study of the competing uses, including, but not limited to, food production, carbon storage in forests, and habitat conservation. Increasing yields of biomass crops above natural yields is another challenging path toward increasing the potential of bioenergy. Based on abandoned lands and current technologies, however, expanding bioenergy crops to offset more than a small fraction of global primary energy consumption will present major challenges and difficult trade-offs.

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