Volume 106
Number 2
Summer 2020

Journal of the

WASHINGTON

ACADEMY OF SCIENCES

1898

ISSN 0043-0439

Issued Quarterly at Washington DC

Washington Academy of Sciences
Founded in 1898

Journal of the Washington Academy of Sciences (ISSN 0043-0439)

Published by the Washington Academy of Sciences
email: wasjournal@washacadsci.org
website: www.washacadsci.org

The Journal of the Washington Academy of Sciences

The *Journal* is the official organ of the Academy. It publishes articles on science policy, the history of science, critical reviews, original science research, proceedings of scholarly meetings of its Affiliated Societies, and other items of interest to its members. It is published quarterly. The last issue of the year contains a directory of the current membership of the Academy.

Subscription Rates

Members, fellows, and life members in good standing receive the Journal free of charge. Subscriptions are available on a calendar year basis, payable in advance. Payment must be made in US currency at the following rates.

US and Canada	$30.00
Other Countries	$35.00
Single Copies (when available)	$15.00

Claims for Missing Issues

Claims must be received within 65 days of mailing. Claims will not be allowed if non-delivery was the result of failure to notify the Academy of a change of address.

Notification of Change of Address

Address changes should be sent promptly to the Academy Office. Notification should contain both old and new addresses and zip codes.

Postmaster:

Send address changes to WAS, Rm GL117,
1200 New York Ave. NW
Washington, DC 20005

Academy Office
Washington Academy of Sciences
Room GL117
1200 New York Ave. NW
Washington, DC 20005
Phone: (202) 326-8975

Volume 106
Number 2
Summer 2020

Journal of the

WASHINGTON

ACADEMY OF SCIENCES

1898

ISSN 0043-0439

Issued Quarterly at Washington DC

EDITOR'S COMMENTS

Presenting the 2020 summer issue of the *Journal of the Washington Academy of Sciences*.

There are four papers in this issue plus two interesting Science Bites. First up is an astronomy paper on dark energy in the Local Group. To follow is a study of the land print of the US and the extinction of species. Then a study of industry-academic collaborations. And ending with a study of how to get a great kick in football. We are lucky to have two Science Bites: one on 3D printing and one on GPS.

Please consider submitting short (typically one page) papers on an interesting tidbit in science. There are a lot of interesting tidbits out there. Every science field has them. They sit in your brain ready to share. We all want to learn about things in fields other than our own. So pile them up and send them in.

The Journal is the official organ of the Academy. Please consider sending in technical papers, review studies, announcements, SciBites, and book reviews. Send manuscripts to wasjournal@washacadsci.org. If you are interested in being a reviewer for the *Journal*, please send your name, email address, and specialty to the same address. Each manuscript is peer reviewed, and there are no page charges. As you can tell from this issue we cover a wide range of the sciences.

I encourage people to write letters to the editor. Please send by email (wasjournal@washacadsci.org) comments on papers, suggestions for articles, and ideas for what you would like to see in the Journal. I also encourage student papers and will help the student learn about writing a scientific paper.

I hope everyone is safe and healthy in this time of pandemic.

Sethanne Howard

Journal of the Washington Academy of Sciences

Editor Sethanne Howard showard@washacadsci.org

Board of Discipline Editors

The *Journal of the Washington Academy of Sciences* has a twelve member Board of Discipline Editors representing many scientific and technical fields. The members of the Board of Discipline Editors are affiliated with a variety of scientific institutions in the Washington area and beyond — government agencies such as the National Institute of Standards and Technology (NIST); universities such as Georgetown; and professional associations such as the Institute of Electrical and Electronics Engineers (IEEE).

1898

Washington Academy of Sciences
1200 New York Avenue
Rm G119
Washington, DC 20005

Please fill in the blanks and send your application to the address above. We will contact you as soon as your application has been reviewed by the Membership Committee. Thank you for your interest in the Washington Academy of Sciences.

(Dr. Mrs. Mr. Ms)_

Business Address

Home Address

Email

Phone ______________________________

Cell Phone ______________________________

preferred mailing address | Type of membership

____Business ____Home | ____Regular ____Student

Schools of Higher Education attended	Degrees	Dates

Present Occupation or Professional Position ______________________
Please list memberships in scientific societies – include office held

Instructions to Authors

1. Deadlines for quarterly submissions are:

Spring – February 1	Fall – August 1
Summer – May 1	Winter – November 1

2. Draft Manuscripts using a word processing program (such as MSWord), not PDF. We do not accept PDF manuscripts.
3. Papers should be 6,000 words or fewer. If there are seven or more graphics, reduce the number of words by 500 for each graphic.
4. Include an abstract of 150-200 words.
5. Use Times New Roman, font size 12.
6. Include two to three sentence bios of the authors.
7. Graphics must be easily resizable by the editor to fit the Journal's page size. Reference the graphic in the text.
8. A full page in the Journal is 6.5 x 9″. This includes the margins and headers and footers.
9. Use endnotes or footnotes. The bibliography may be in a style considered standard for the discipline or professional field represented by the paper.
10. Submit papers as email attachments to the editor or to wasjournal@washacadsci.org .
11. Include the author's name, affiliation, and contact information – including postal address. Membership in an Academy-affiliated society may also be noted. It is not required.
12. Manuscripts are peer reviewed and become the property of the Washington Academy of Sciences.
13. There are no page charges.

Washington Academy of Sciences Affiliated Institutions

National Institute for Standards & Technology (NIST)

Meadowlark Botanical Gardens

The John W. Kluge Center of the Library of Congress

Potomac Overlook Regional Park

Koshland Science Museum

American Registry of Pathology

Living Oceans Foundation

National Rural Electric Cooperative Association (NRECA)

Calculating Local Group Dark Energy using Better Mass Data: Cosmological (and Pedagogical) Results

G. Byrd* and P. Teerikorpi**

*Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL
**Tuorla Observatory, Department of Physics and Astronomy,

Abstract

The Local Group (LG)'s mass is mostly in Andromeda (M31) and the Milky Way (MW), a central 0.75 Mpc (2.4 MLY) bound binary of mass M. Dark energy (DE) density "antigravity" causes an outward acceleration (greater with radius R) of the dwarf population relative to M's inward gravitation. The LG's dwarfs show an increasing outer velocity (V) component with R in observations. We compare the data to a local theoretical curve using cosmologically estimated "ΛCDM" values. Observations by the WMAP and others give a value of 1.0803 for the critical density (universe expands forever). The cosmologically determined DE density is ~0.7 of critical density. The MW–M31 binary mass can be estimated from their first moving apart nearly radially and now approaching. We choose a more recent LG mass~$4x10^{12}$ to calculate a V vs R line using the cosmologically determined ΛCDM DE density. An excellent fit to the data is obtained. Smaller masses give poorer fits. Assuming the DE = 0 and mass $4x10^{12}$, gives a bad fit to the data. It appears the DE local density is the same as found cosmologically with no support for variation with time. DE acceleration in the Local Group provides an alternative and perhaps more convincing demonstration on a local scale for students than cosmological estimates.

Introduction

WE FIRST BRIEFLY REVIEW how dark energy's (DE's) existence and value is inferred "cosmologically" from distant galaxies using Ia supernovae and analysis of CMB anisotropies. Alternative explanations requiring no dark energy typically refer to large scales with expected DE effects on small scales. In light of these results, expected non-zero DE effects on dynamics in the Local Group (LG) can be an important test of the cosmologically obtained model.

Cosmologically Deduced Dark Energy

Dark energy was discovered observationally by studying distances and redshifts of galaxies at impressively large cosmic look-back times into the past (Riess *et al*. 1998, Perlmutter *et al*. 1999). The primary methods use white dwarf supernovas to estimate the large light travel time distances of galaxies. Shift of recession is a fraction of the speed of light, $z = (\lambda_{observed} - \lambda_{emitted}) / \lambda_{emitted}$. The method compares intensity (apparent magnitude) and known luminosity (absolute magnitudes) to estimate distances.

The well-known linear Hubble Law expresses redshift velocities ($V = cz$) versus light travel distances, D, of "nearby" galaxies. Here c is the speed of light and z is the fractional redshift. Figure 1 shows a plot of these two quantities for nearby galaxies from Reiss *et al* (1998). This graph portrays the concept of the expanding universe. Among the plotted points a straight line from point one at $V = 0$, $D = 0$ to point two is drawn among data points in a best fit. For this example, the slope gives a Hubble Constant, $H_o = V/D \approx 65000/940 = 69$ (km/s)/Mpc. Here 1 Mpc =3.26 million light years.

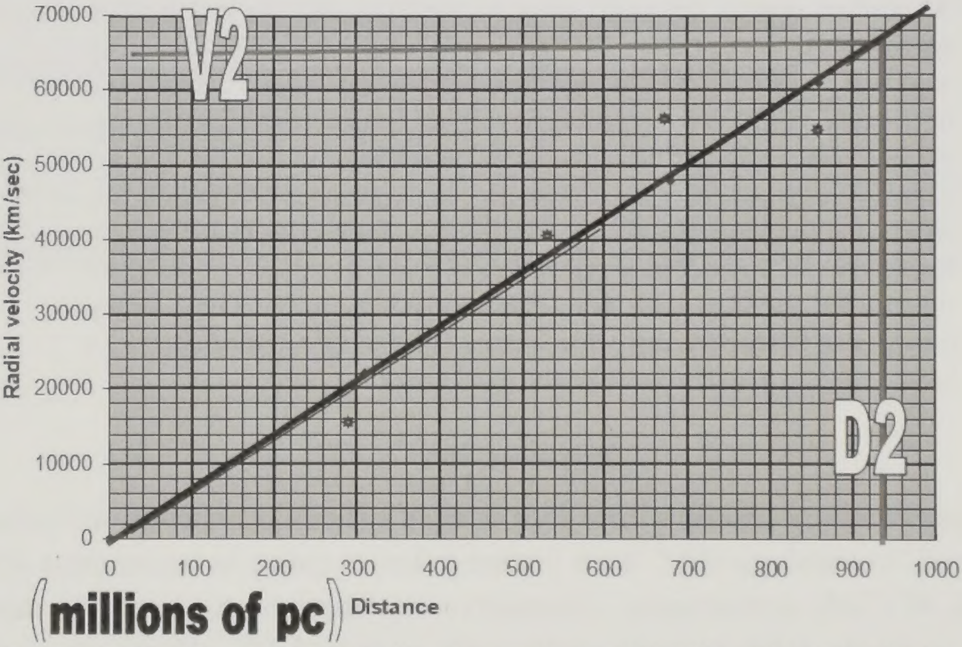


Figure 1. The linear Hubble Law expresses redshift velocities (cz) versus light travel distances of "nearby" galaxies from Reiss *et al* (1998).

The expansion of the universe had its inception in a big bang which would be slowed by the mutual gravitational attraction of its contents. Using many nearby galaxies, much effort was made to find the Hubble constant slope and any curvature of the plot due to gravitation. Data for much more distant galaxies was sought to measure the matter content of the universe.

A Riess *et al.* 1998, Perlmutter *et al.* 1999 data plot is given in Figure 2. The curve represents a uniformly expanding universe with no gravitational slowing or repulsion. There is a bit of curvature due to relativity. Mathematically the light travel (proper) distance $d=(cz/H_0)(1+z/2)/(1+z)$ for the Milne model. See Byrd *et al.* (2012) and Irwin (2008). If there is only gravitating matter deceleration, distant galaxies should be above the curve. As can be seen in Figure 2, the majority of observed distant points are below the curve. The observations in the graph indicate properties that are progressively more distant in the past. From the distributions of data points the acceleration due to "dark energy" DE began to dominate ~6-7 billion years ago.

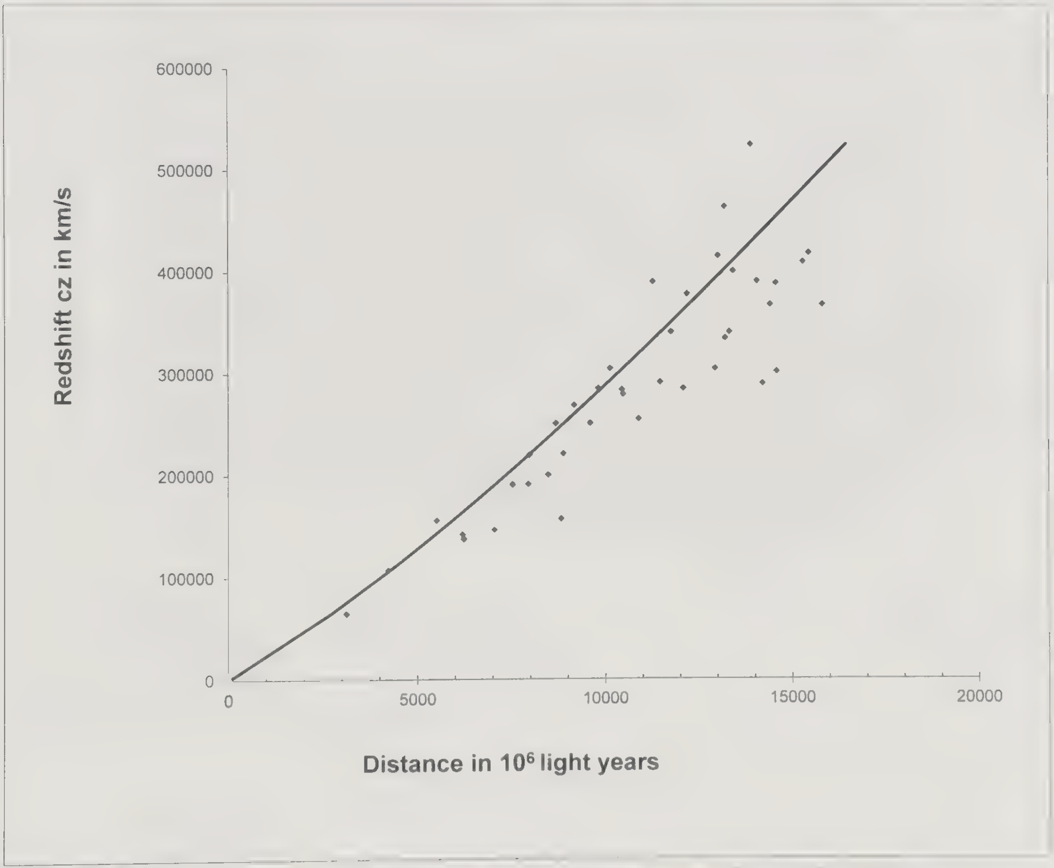


Figure 2. Non-linear Redshifts at Large Distances found by Type I supernovae from Riess *et al.* (1998) and Perlmutter *et al.* (1999).

To give notation and values for the variables, we use the microwave background 3K "ΛCDM" values from WMAP (see references Technical Papers and Cosmological Parameters). The critical density is

$$\rho_c = 9.5\times10^{-30}\,\mathrm{g/cm^3} = 3H_0^2/(8\pi G).$$

This density is 1.0803 ± 0.085 of the critical flatness density (in which the universe expands forever) which is designated as $\Omega = 1$. Current energy densities are DE $\rho_v = 7\times10^{-30}$ g/cm^3 and matter $\rho_m = 3\times10^{-30}$ g/cm^3 corresponding to $\Omega_v = 0.7$ and $\Omega_m = 0.3$. The age of the universe =13.75 billion years. The Hubble constant $H_o = 71$ (km/s)/Mpc.

As shown in Figure 3, a better fit to the data points requires a DE acceleration to have the points below the line. Gravitating matter tends to reduce the effect of DE. The model passing through the middle of the SN Ia points has both DE and gravitating matter. From Irwin (2007), $q = \frac{\Omega m}{2} - \Omega_V$ for z < 0.5 with $\Omega_v = 0.7$ and $\Omega_m = 0.3$ for the sum = 1 for the critical density and using

$$d = (\mathrm{Eq}\,F.16)/(1+z) = (cz/H_0)\left[1+z(1-q)/2\right]/(1+z).$$

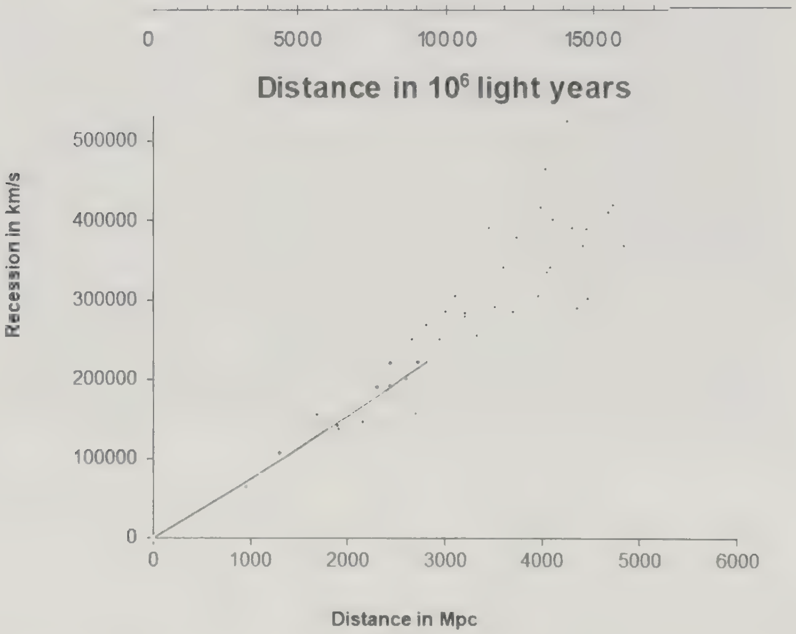


Figure 3. A better fit to the recession versus distance data points with a DE acceleration to have the points below the line. This is interpreted as cosmological evidence for dark energy.

Calculating Local Group Dark Energy using Better Mass Data:

By examining Figure 4 we can see that most of LG's gravitating mass (M) is in a 0.75 Mpc central binary. Members M31 and MW orbit the center of mass (CM). Many dwarf galaxies are left beyond the binary from formation, others are bound to it. There are also a few low mass galaxies.

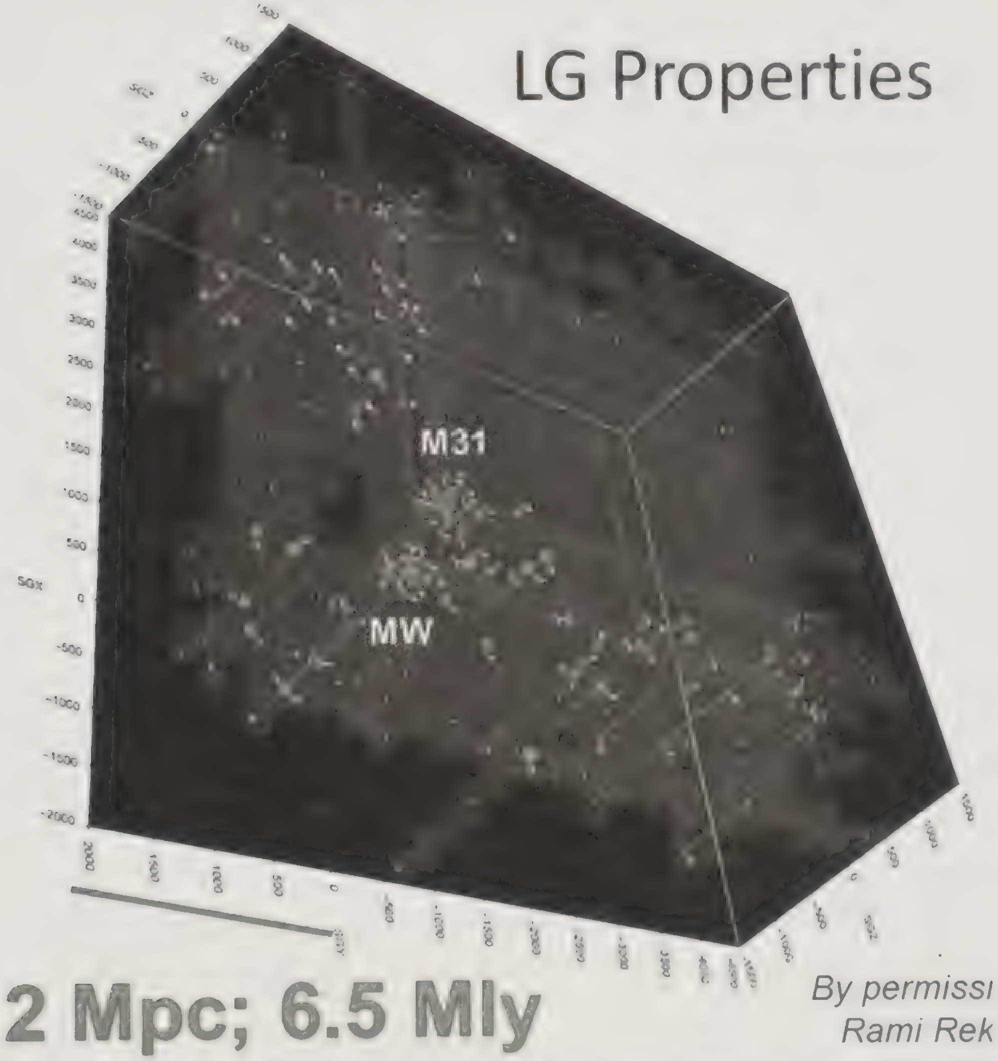


Figure 4. Plot of Local Group members. By permission of Rami Rekola.

Local Group Dwarf Equation of Motion and Observations

As diagrammed in Figure 5, in and near the binary center of mass, dwarf galaxy motions are inward and outward in and near the binary CM (red/blue arrows). At distance *R* outside the binary, motions are outward (red). Relative to the CM, a dwarf's equation of motion is the central binary mass, *M*, gravitational attraction plus the DE density, ρ_v, repulsion:

$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_v R.$$

The net acceleration ≈ 0 at R equals

given by the local "Newtonian" limit of general relativity with DE. (Byrd *et al.* 2012).

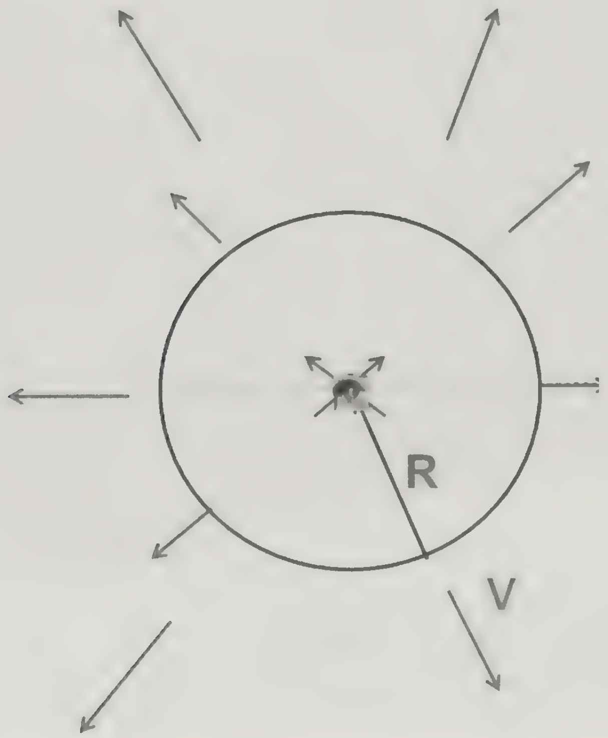


Figure 5. Dwarf motions relative to the binary center of mass (CM) are shown. Motions are inward and outward in and near the binary CM (arrows). At *R* outside the binary, motions are outward (red) relative to CM.

Figure 6 shows dwarfs' observed recession velocities relative to center of mass of binary versus radius, Chernin *et al.* (2009) and

Karachentsev *et al.* (2009). The line is an empirical fit to an outer dwarf outflow region. The gravitationally bound central region shows inner and outer (positive and negative) motions.

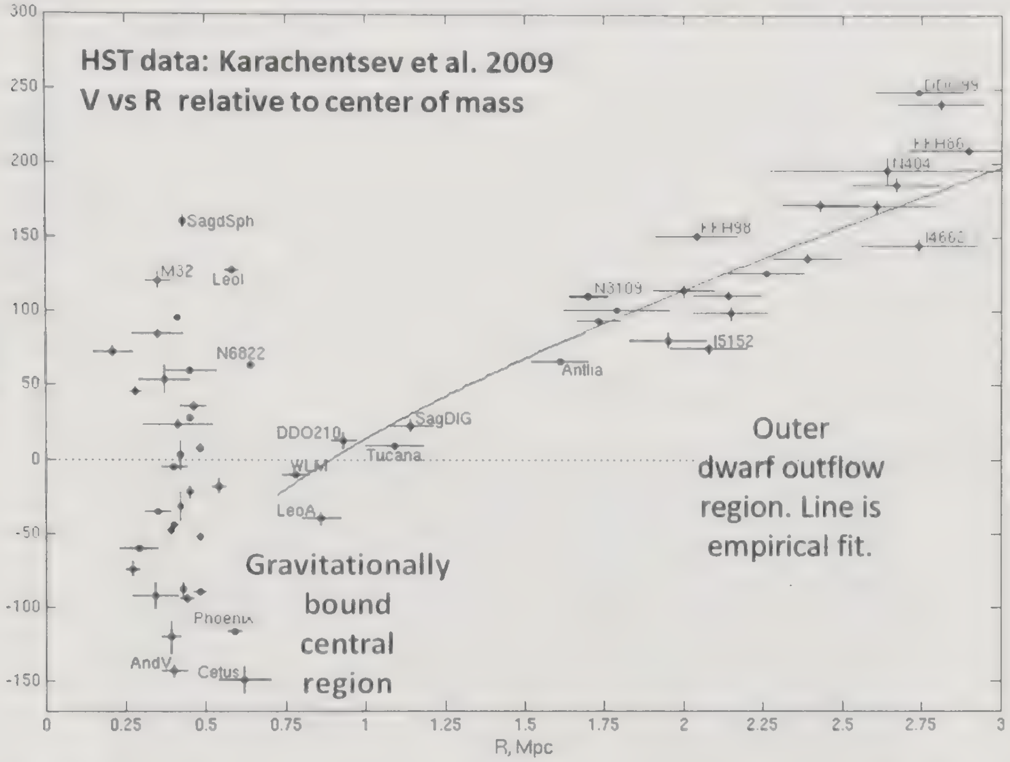


Figure 6. Dwarfs' observed wavelength change velocities relative to center of mass of binary (Chernin *et al. 2*009 and Karachentsev *et al*. 2009).

Determining DE using Observed Outward *V*s at *R*s.

Use Outflow *V* vs *R* in Figure 6 to estimate DE ρ_v. Small members fly out under LG gravity and DE acceleration. Integrate each dwarf's equation of motion from small to present-day R & V. Mathematically we get

$$\frac{V}{H_v R_v} = \left[\left(\frac{R}{R_v} \right)^2 + \frac{2}{R / R_v} - 2\alpha \right]^{1/2}$$

where the small initial energy;

$$E = -\frac{\alpha G M}{R_v}, \ R_v = \left(\frac{3M}{8\pi\rho_v} \right)^{1/3} \approx 1 \text{ Mpc and } H_v = \left(\frac{8\pi G \rho_v}{3} \right)^{1/2}.$$

The subscript *v* indicates dark energy.

The time to reach from near the center to the present must be the approximate age of universe or

$$t = \int_0^R V^{-1} dR = 13.7\,\text{Gyr} = \frac{1}{H_v} \int \left[\left(\frac{R}{R_v} \right)^2 + \frac{2}{R/R_v} - 2\alpha \right]^{-1/2} d\frac{R}{R_v}.$$

In the above equation choose different dark energy densities, ρ_v, to fit *V* vs *R* data from Hubble Space Telescope and the Gaia mission to obtain *M*. This permits an improvement in LG mass. The transverse motion of M31 has now been measured (van der Marel *et al.* 2019) which permits a better mass measurement (McLeod *et al*, 2017). As seen in Figure 7, M31 and MW receded from one another in the past. The future approach path to merger is shown. The revised mass estimate is $M = 3.6 \pm 0.3 \times 10^{12}\ M_\odot$.

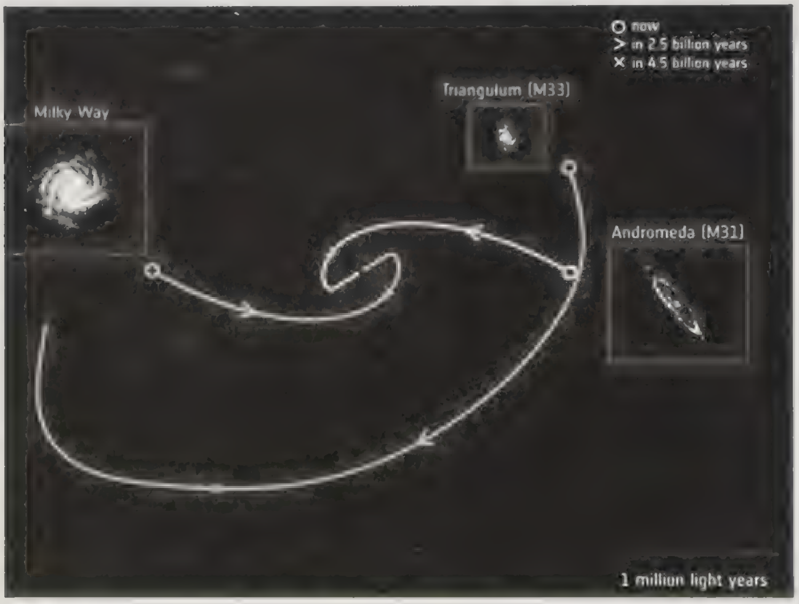


Figure 7. Future path to merger of the Milky Way Galaxy and M31. https://www.esa.int/ESA_Multimedia/Images/2019/02/Future_motions_of_the_Milky_Way_Andromeda_and_Triangulum_galaxies#.XlnMdFILDsA.link

Using better *M* in *V* vs *R* plot to Estimate Local Group DE

As shown in Figure 8, various masses are used to check which one results in the observed outward *V*s at *R*s. There is a good fit to the observed

V versus R where $R > 1.25$ Mpc and the "Cosmological" DE $\rho_v = 7 \times 10^{-30}$ g/cm^3 for the best LG $M = 4 \times 10^{12}$ M⊙.

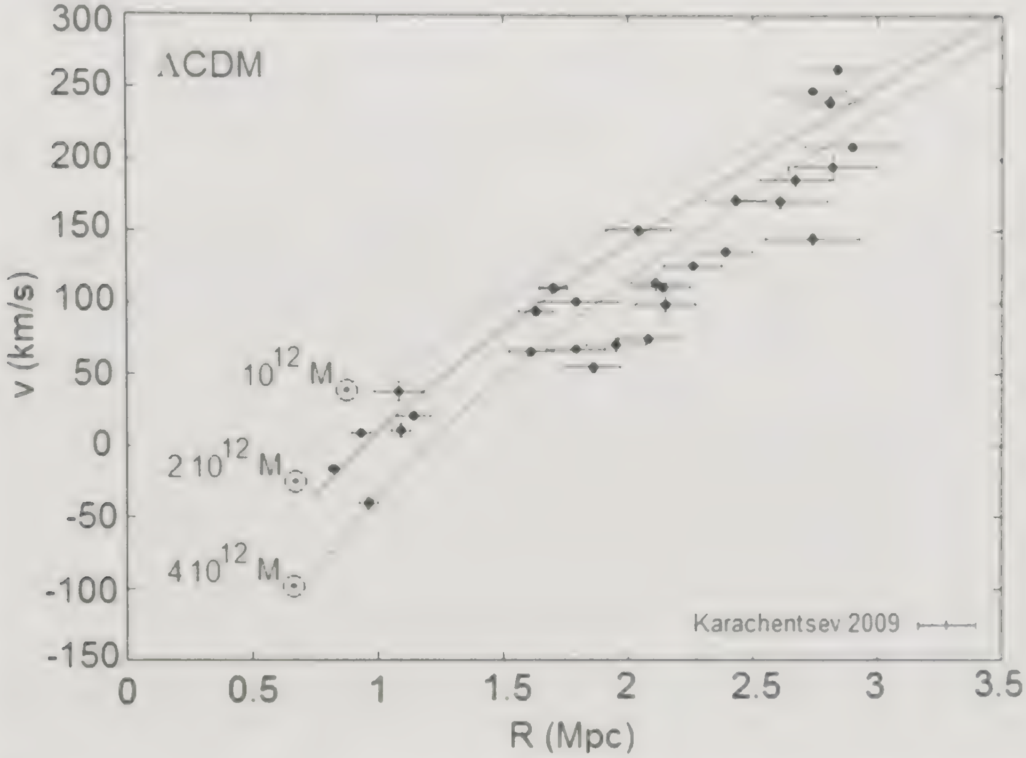


Figure 8. Dwarfs' observed velocities due to wavelength change relative to center of mass of binary (Chernin *et al.*2009 and Karachentsev *et al.* 2009). Saarinen and Teerikorpi, (2014) calculated V versus R value curves for different LG masses and "Cosmological" DE $\rho_v = 7 \times 10^{-30}$ g/cm^3 .

Recall there is a good R, V fit > 1 to 1.5 Mpc with "Cosmological" DE $\rho_v = 7 \times 10^{-30}$ g/cm^3 for the better LG $M = 4 \times 10^{12}$ $M_\odot$. If $\rho_v = 0$ g/cm^3 the best mass 4×10^{12} $M_\odot$ line is a poor fit. The mass 2×10^{12} is a good fit but has too low a mass, two times the estimated uncertainty of 1×10^{12} $M_\odot$ away from the better 4×10^{12} $M_\odot$. Local DE density doesn't appear to be zero. See Figure 9.

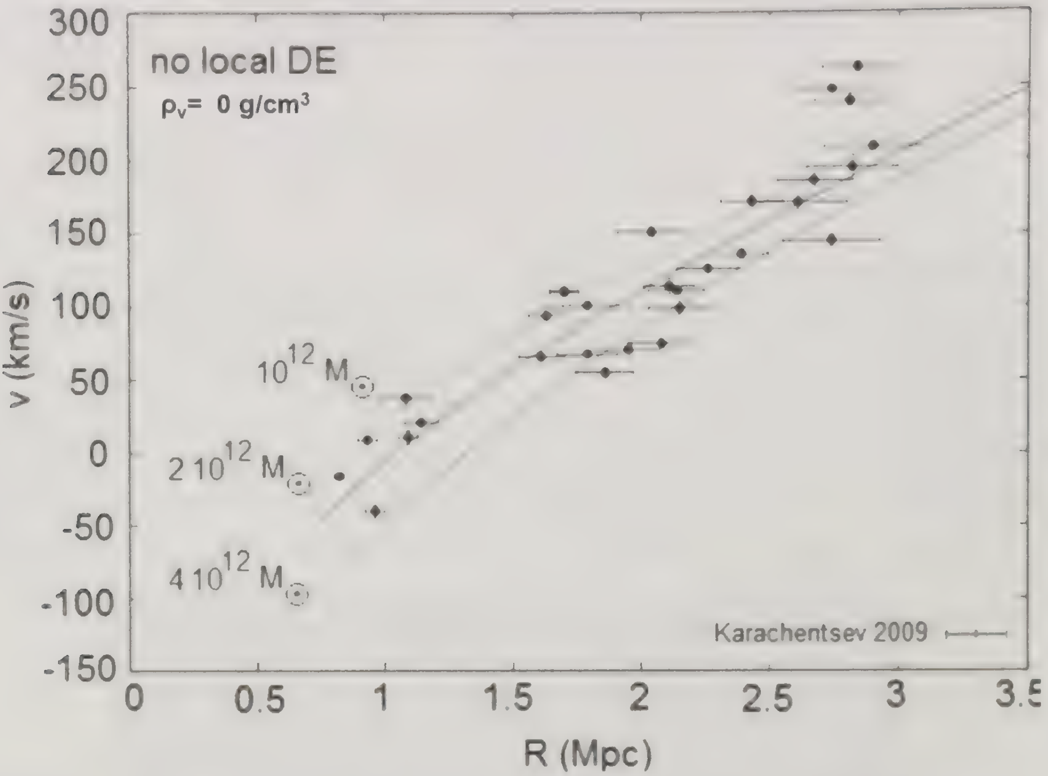


Figure 9—Velocities and for dwarf LG masses and $\rho_V = 0$ g/cm^3. Up-to-date LG mass 4×10^{12} $M_\odot$ line is a poor fit.

Conclusions

The better mass ~ 4×10^{12} $M_\odot$ for the LG and dwarfs' V vs R do not support zero local dark energy (Figure 9). The "local" dark energy estimate is consistent with cosmologically distant estimates (Figure 8). A recent determination using a galaxy survey combined with other methods agrees with the accepted cosmological value, (Nadathur, *et al.* 2020). Also see Byrd *et al* (2015, Sec. 8) for a list of values determined at z as large as 3. Agreement of cosmological and local values implies no change with time indicating there is no future "big rip".

DE acceleration in LG is possibly a more understandable argument for DE than cosmological evidence. Student demonstrations of an expanding dark energy universe follow.

Appendix: Student Demonstrations

"Big Band" Universe Expansion Demonstration. Figure 10a, b shows a large rubber band with a uniform distribution of "Bull Dog" clip "galaxies" and their gravitation. Stretching between hands is "dark energy repulsion". Elastic resistance is of the band is "uniform matter gravitation". As the band is stretched, we see uniform relative motion of the galaxies away from one another. A video link is also given.

Figure 10a, b—A uniform large rubber band with a uniform distribution of Bull Dog clip "galaxies" and their gravitation. Video link. https://drive.google.com/file/d/1782jMilbqeccwyVcymFjBOPYaEfSe6Y3/view?usp=drivesdk

Figure 11a, b shows a large rubber band with an initially uniform distribution of Bull Dog clip "galaxies." However, two massive galaxies have a greater gravitational force represented by an additional strand between them. These represent the Local Group binary members, the Milky Way and M31. Again, stretching between bands is "dark energy repulsion". However, elastic "gravitational" resistance is of the band is non-uniform because it is greater between the binary members. As the band is stretched, we see the binary members hardly moving away from one another and the outer dwarf members receding from the binary at progressively larger distances as "dark energy" stretches space (the band). A video link is also given.

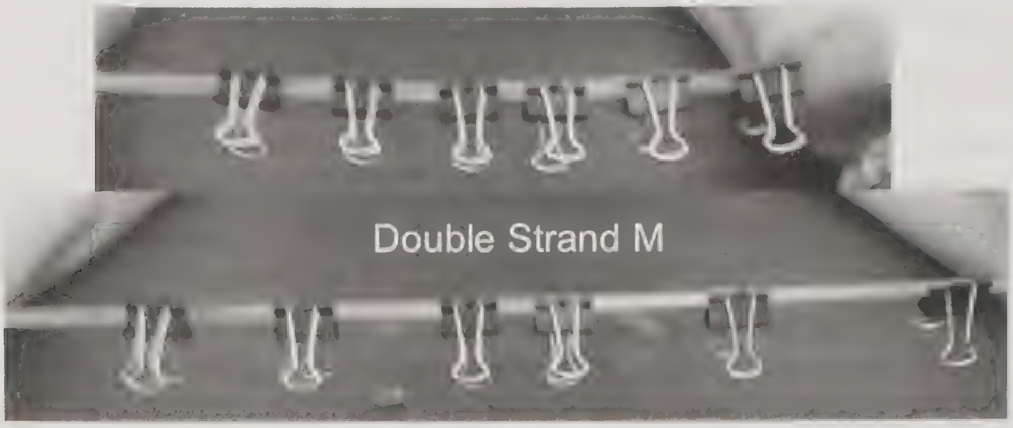


Figure 11a, b -- A large rubber band with an initially uniform distribution of bull dog clip "galaxies." However, two galaxies have a greater gravitational force represented by an additional strand between them. https://drive.google.com/file/d/17O6_eld6Dd9e9YOs9Op2pZ9-FoMjsrxJ/view?usp=drivesdk

References

Byrd, G., Chernin, A. D., Teerikorpi, P. and Valtonen, M. 2012 *Paths to Dark Energy*, De Gruyter, Berlin/Boston, ISBN 978-3-11-025854-7. Sec. 15.1 p. 300

Byrd, G., Chernin, A., Teerikorpi, P. and Valtonen, M. 2015, Review Article: "Observations of General Relativity at strong and weak limits" in *General Relativity: The most beautiful of theories* (De Gruyter Studies in Mathematical Physics) 2015. ISBN-10: 3110340429; ISBN-13: 978-3110340426

Chernin, A.D., Bisnovatyi-Kogan, G. S., Teerikorpi, P., Valtonen, M. J., Byrd, G. G. and Merafina, M. 2013 "Dark energy and the structure of the Coma cluster of galaxies," *Astronomy and Astrophysics*, **553** (2013), A101:1–A101:4.

Chernin, A. D., Teerikorpi, P.,Valtonen, M. J., Dolgachev, V. P., Domozhilova, L. M. and Byrd, G. G. 2009 " Local dark matter and dark energy as estimated on a scale of ~ 1 Mpc in a self-consistent way" *Astron. & Astrophys.*, **507**, 1271. (and references

https://www.esa.int/ESA_Multimedia/Images/2019/02/Future_motions_of_the_Milky_Way_Andromeda_and_Triangulum_galaxies#.XlnMdFILDsA.link

Irwin ,J. 2007 *Astrophysics: Decoding the Cosmos* John Wiley and Son, West Sussex, England ISBN 978-470-01306-9.

Karachentsev, I.D., Kashibadze, O.G., Makarov, D.I., Tully, R.B. 2009, *MNRAS*, **393**, 1265 https://arxiv.org/pdf/0811.4610.pdf

https://ned.ipac.caltech.edu/cgi-bin/objsearch?search_type=Search&refcode=2009MNRAS.393.1265K

McLeod, M. and Libeskind, N. and Lahav, O. & Hoffman, Y. 2017, Dec. "Estimating the Mass of the Local Group Using Machine Learning" *Journal of Cosmology and Astroparticle Physics* **34**. https://arxiv.org/pdf/1606.02694.pdf

Nadathur, S., Percival, W. J., Beutler, F., Winther,, H, A. 2020, *Physical Review Letters*. Phys. Rev. Lett. **124**, 221301 DOI: 10.1103/PhysRevLett.124.221301 Also see https://scitechdaily.com/most-precise-tests-of-dark-energy-and-cosmic-expansion-yet-confirm-the-model-of-a-spatially-flat-universe/

Perlmutter *et al*. 1999, *The Astrophysical Journal*, **517**, 565-586

Riess, A. G. *et al* 1998 *The Astronomical Journal*, **116**, Issue 3, 1009 https://arxiv.org/abs/astro-ph/9805201

Saarinen, J. and Teerikorpi, P. 2014, *Astronomy and Astrophysics*, **568**, A33

van der Marel, R.P.,Fardal, M. A., Sohn, T. S., Patel, E., Besla, G., del Pino, A., Sahlmann, J. and Watkins, L. L. 2019 *The Astrophysical Journal*, **872,** 24 https://iopscience.iop.org/article/10.3847/1538-4357/ab001b

WMAP Technical papers can all be found at: http://lambda.gsfc.nasa.gov/product/map/current/map_bibliography.cfm

WMAP Cosmological Parameters based on the latest observations:

http://lambda.gsfc.nasa.gov/product/map/current/parameters.cfm

BIO

Gene Byrd (B.S Texas A&M Univ. 1968; PhD 1974 the Univ. of Texas) is a Professor of Astronomy (emeritus) at the Univ. of Alabama. He studies the dynamics of galaxies, discovering the pattern in NGC4622, which, counter-intuitively, has inner and outer spiral arms winding in opposite directions See https://www.researchgate.net/profile/Gene_Byrd2 .

Pekka Teerikorpi received his doctorate at the University of Turku (1981). After teaching and research positions there he is now a retired adjunct professor. He studies extragalactic astronomy, in particular, the cosmic distance scale, the expansion of the universe (the Hubble constant) and dark energy.

Land Footprint of the United States of America

AARON S. HOGUE

Salisbury University

ABSTRACT

Globally more than a quarter of all evaluated species are threatened with extinction, and the numbers continue to grow. Studies suggest habitat loss, driven predominantly by human land use, is the primary cause. The goals of this study are to examine the contribution of the United States of America (US) to habitat loss by quantifying its domestic land footprint (area of land altered from its natural state for human use), and to identify changes in human behavior that can reduce this footprint. Land use data for the US were compiled for the focal year 2012 and partitioned into 14 consumption categories. When all combined, the domestic land footprint in 2012 was 5,510,576 km^2, an area equivalent to 72% of the contiguous US. Although this is likely an underestimate (for reasons outlined below), if everyone on earth averaged the per capita footprint of Americans, the global human land footprint would exceed all ice-free land on Earth. Thus, the US population damages ecosystems on scales vastly greater than what is proportional or sustainable. Of the total domestic land footprint 71% is for meat/animal production. Given it takes 4-140 times more land to produce the same amount of protein and calories from meat as it does from plants, replacing meat with plant protein could eliminate the majority of the US land footprint, exceeding the land savings of all other conceivable actions combined.

INTRODUCTION

OF THE SPECIES THAT HAVE BEEN EVALUATED over 30,000 are threatened globally with extinction, due primarily to the actions of humans (IUCN 2020). That's more than one quarter of all species assessed (IUCN 2020). The severity of this crisis is reinforced by a consideration of recent extinctions. A number of studies comparing recent rates of extinction (largely driven by human activity) to background rates documented in the fossil record suggest current rates are hundreds of time higher than normal, placing us in the midst of one of the six greatest mass extinction events in earth history (Leakey & Lewin 1992; Dirzo & Raven 2003; Barnosky *et al.* 2011).

Recognition of the urgent need for action led to the global ratification of the Convention on Biological Diversity (CBD) in 1992. The goal of this and subsequent international efforts was to significantly reduce rates of biodiversity loss, with specific targets for both 2010 and 2020 (Hoffmann *et al.* 2010; Tittensor *et al.* 2014). Despite these efforts, an examination of 31 indicators established to evaluate biodiversity declines found no significant reduction in rates of decline, and an overall failure to achieve the 2010 Target (Butchart *et al.* 2010). A detailed analysis of birds, mammals, and amphibians in the years leading up to 2010 (1980-2008) found all three groups showed net increases in the probability of extinction with, on average, 52 species moving "1 Red List category closer to extinction" per year (Hoffmann *et al.* 2010). Similarly, a mid-term analysis of progress toward the 2020 Target found biodiversity declines continue, and projected that the 2020 Target also will not be achieved (Tittensor *et al.* 2014). Subsequent work has continued to find substantial reductions in population sizes, species ranges, and biodiversity across the globe (Ceballos *et al* 2017; Grooten & Almond 2018), leading Ceballos *et al.* (2017) to describe the current state of affairs as an unprecedented "biological annihilation." Not only does this mean the future of large numbers of species remains very much in doubt, but as more species disappear from ecosystems, this will, in turn, have profound negative impacts on the health of these ecosystems and the human populations that depend on them (Cardinale *et al.* 2012; Hooper *et al* 2012).

Given the gravity of the situation, it is important to act swiftly and reduce the major factors responsible for these biodiversity declines. And what are these major factors? A number of studies have attempted to answer this question using data from the International Union for the Conservation of Nature (IUCN). The IUCN is the World's pre-eminent global conservation body, and maintains the Red List, the single most authoritative and comprehensive list of all species scientifically identified as threatened with extinction (IUCN 2020). Contrary to the near single-minded focus by the US media and political elite on climate change, analyses of this database and other sources have consistently found habitat loss exceeds other threats as the most significant (Venter *et al.* 2006; Vie *et al.* 2009; Pereira *et al.* 2012; Tittensor *et al* 2014; Grooten & Almond 2018). More specifically, it is human land use that poses the greatest threat to species (Tittensor *et al.* 2014; Maxwell *et al.* 2016).

It is beyond the scope of this work to review the status of the Earth's ecosystems, but to give some sense of the extent of human impact, 53% of

Earth's ice-free land has been modified from native ecosystems to human-dominated landscapes (Hooke *et al.* 20012) and 75% of land area globally has been measurably impacted by human activities (Venter *et al.* 2016). Most of the remaining 25% of minimally disturbed land consists of low biodiversity deserts, tundra, and boreal forests. As the global population is projected to increase from 7.7 billion to 11 billion by the end of the century (United Nations 2019), with each additional person requiring more land for food, energy, space, and other resources (Gibbs *et al.* 2010; d'Amour *et al.* 17), this means habitat loss and ecosystem degradation from additional land conversion will continue to grow unless we identify strategies to reduce the problem.

An important part of moving in the right direction on land use involves several things: quantifying current land use, determining which human activities require the most land, and identifying practical changes in human activities that can significantly reduce the need for land. Nowhere is this more important than in the US. The US has a vastly higher environmental impact than nearly every other country on the planet, both on a per capita and national basis (Bradshaw *et al.* 2010; Simas *et al.* 2017), so changes in this country can yield dramatic reductions in land use and habitat loss. The purpose of this study is to use a variety of data sources to obtain a minimum, conservative estimate of the amount of land within the US significantly impacted by human activities and partition it into discrete categories reflecting specific aspects of American culture (America and American as used herein are meant to refer to the United States and its population). These data will then be used to identify concrete, yet feasible actions that can dramatically lessen the environmental impact of the US. The focus was limited to domestic land footprint data because adequate, accurate data for most imports and US activities abroad were not available. Given the hundreds of foreign US military bases (Vine 2015), and the fact that there was a $537 billion trade deficit in the focal year of this study (US Census Bureau 2019), the overall footprint computed is likely an underestimate of our actual footprint.

METHODS

Primary data sources were limited to the most accurate, most comprehensive available for the year 2012 that provide as close to a full picture as possible of the minimum footprint of US Citizens without double counting. The year 2012 was selected because it was the only recent year for which several comprehensive datasets were simultaneously available: a GIS database partitioning land into discrete use categories (residential, transportation, commercial, *etc.* – Theobald 2014) and several infrequently released government databases containing land use information. The latter included the 2012 Grazing Statistical Summary (USDA 2013), 2012 Agricultural (Ag) Census (USDA 2014), 2012 Natural Resources Inventory (USDA 2015), and the 2012 Forest Resources of the United States (Oswalt *et al.* 2014). These datasets served as the starting point for all footprint calculations, with refinements derived from other governmental and nongovernmental sources noted below. Only lands modified from their natural state for human use were included in the footprint calculations (*e.g.*, lands for buildings, roads, lawns, timber harvests, grazing, crops). The footprint calculations do not include lands indirectly impacted by human activity, such as habitat degradation due to fragmentation or wildlands burned by human-caused fires. It is therefore a conservative estimate of the United States' most direct and most significant impact on domestic terrestrial ecosystems. Based on these and other sources, land footprint data largely fell into two major categories: Non-Biomass Developed Land and Biomass Production Land. Each of these two main categories and associated sub-categories are described separately below.

Non-Biomass Developed Land

Developed land consists of built land (*e.g.*, buildings, concrete, asphalt), but may also include some surrounding open areas created and maintained by humans (*e.g.*, mowed turfgrass). The most thorough source for total area of developed land in 2012 is the National Resources Inventory, or NRI (USDA 2015). The NRI is a scientifically robust inventory of non-Federal US lands based on a rotational sampling of 800,000 points spread across the US and its territories, using both satellite imagery and on-the-ground verification by Natural Resource Conservation Service (NRCS) staff. The only other data source that approaches the thoroughness of the NRI is the 2011 National Land Cover Database, or NLCD (Homer *et al.*

2015). The NLCD differs from the NRI in that it relies exclusively on identifying land cover from high resolution (30x30 meter) satellite imagery. Both datasets yield very similar numbers (differing by less than 1% in overlapping areas), but given the NLCD is from 2011, not 2012, and is exclusively satellite-based without ground verification (the lack of which tends to underestimate developed land – Theobald 2014), the NRI is used as the primary source, with the NLCD used to fill gaps in the NRI database. One such gap is that the NRI does not quantify developed land in Alaska or federal properties. To partially fill this gap estimates of developed land for Alaska and federal military bases in the conterminous US were obtained from the NLCD (using the partitioning process described below) and added to the NRI data to obtain an estimate of total US developed land. As the NLCD data are from the year prior, and do not include all federal lands, this total must be viewed as an underestimate of total developed land in 2012.

One limitation of both the NRI and NLCD is that they do not partition developed land according to more specific land use categories. While this limitation cannot be completely overcome, the use of an additional dataset in combination with the NLCD allows one to subdivide a significant fraction of developed land, at least in the conterminous US. Theobald (2014) used US Census data and other sources for the conterminous US to categorize the same 30x30m blocks examined in the NLCD as belonging to one of 80 land use categories. The resulting National Land Use Database (NLUD) was then used to estimate America's land footprint within the conterminous US (Theobald 2014). Unfortunately, this approach overestimates our direct land footprint because census-designated property boundaries for many land uses (*e.g.*, residential, commercial) may contain a mixture of both human-modified and natural land covers, such as built land and forest, respectively. However, by combining these two datasets, it is possible to partition satellite-designated developed land into more discrete land uses.

This was accomplished by using ArcGIS 10.3 to cross-tabulate each 30x30m plot designated as developed in the NLCD with its land use designation in the NLUD. Area measures for similar land use (LU) codes were then combined into one of the following 10 categories (LU codes from Theobald 2014): Water use/access (*e.g.*, boat ramps, hardened shorelines, dams; LU codes 111-172,419, 519,522-523), Outdoor Recreation &

Resources (*e.g.*, parks, golf courses; LU codes 341,410-417,421-422,518,532), Conservation (*e.g.*, nature reserves, archaeological sites; LU codes 511-516,521,531), Residential (*e.g.*, housing; LU codes 211-215), Commercial (*e.g.*, offices, stores; LU codes 221-223), Industrial (*e.g.*, factories, mines; LU codes 231,330), Institutional (*e.g.*, schools, hospitals, government buildings; LU codes 241-249), Major Transportation (*e.g.*, airports, major highways and railways; LU codes 251-255), Crop Infrastructure (*e.g.*, equipment storage, access roads; LU codes 310-311,313-314), and Livestock Infrastructure (*e.g.*, barns, confined animal feeding facilities; LU codes 233,312,315,321). All developed plots not falling into one of the above 10 categories, as well as all developed areas in Hawaii and Alaska (which were not included in the NLUD), were designated as "Unassigned." Crop Infrastructure, Livestock Infrastructure, and Unassigned lands were then subtracted from total developed land to yield known Non-Biomass Developed Land. Note: Major Transportation does not include most small roads or railways. The width of these linear features is often well under 30m, so they tend to be subsumed under the adjacent land use. Thus, it should be assumed that the other developed land categories include their own fraction of transportation land (*e.g.*, residential area includes driveways and often residential roads).

Biomass Production Land

Biomass Production Land consists of land needed to generate products that are grown (*e.g.*, crops, animals, timber). It includes non-developed land used to grow or feed these organisms, as well support lands, many of which fall under the developed land categories "Crop Infrastructure" and "Livestock Infrastructure" noted above. Source data for calculating Biomass Production Land are largely grouped under three land use categories: timberland, cropland, and grazing land. However, these categories do not adequately correspond to final end uses by people that would inform changes in behavior that reduce our environmental impact. For example cropland is used to make very different things, such as fiber, fuel, and food. Therefore, data from these initial three categories were processed to yield six new product categories grouped into two main subcategories. The first main subcategory is Fuel and Fiber Land, which is divided into four product categories: Wood Production Land (from timber land data), Cropland for Fiber, Cropland for Fuel, and Cropland for

Horticulture (from the cropland data). The second main subcategory is Food Production Land, which is divided into Cropland for Food (direct human consumption, from cropland data), and Meat Production Land (which includes Cropland for Feed and grazing lands). Each is described below, organized principally by land use source data due to the interconnectedness of their calculations. However, results will be presented by the main subcategories and six final product categories noted above.

Timberland (Wood Production Land)

The focus of this study is on lands significantly impacted by human activity in 2012. Most forests take many decades to return to mature conditions, let alone natural old growth conditions after harvest (Aide *et al.* 2001; Dunn 2004; Meli *et al.* 2017). Consequently, forests harvested many years prior to 2012 may still be viewed as significantly impacted, even if natural regrowth is occurring. There are data on deforestation rates in the US in the 12 years leading up to and including 2012, averaging 21,995 km^2 per year (Hansen *et al.* 2013). If one adopts a conservative assumption that only forests under 20 years of age continue to show significant human impact (which is without question an underestimate), one could extrapolate this figure over the prior two decades to obtain total impacted forest land (439,907 km^2). However, this does not account for that fact that some of these were converted to other land uses over that time, and are therefore already counted in footprint data for those other categories. Fortunately, the USDA maintains data on total area of forest in 2012 that was either cut that year or under 20 years of age in 2012. These data were used for wood production land. It is important to note, this doesn't include major portions of the 263,837 km^2 of artificially planted forests in the US (Oswalt *et al.* 2014) that were 20+ years old, particularly monoculture and non-native tree plantations, all of which qualify as land significantly modified for human use. Adequate data were not available to include these additional lands in the analyses. Thus, this is an underestimate of forest land significantly impacted by humans.

Cropland

In order to determine the amount of land devoted to producing feed (consumed by livestock), fiber (*e.g.*, cotton, tobacco), biofuels (ethanol and biodiesel), and food (crops fed to humans), it was first necessary to calculate two numbers: total harvested cropland and total non-harvested cropland. These numbers were obtained from the 2012 Agricultural Census (USDA 2014). Total harvested cropland is the amount of land planted and harvested. Non-harvested cropland consists of other cropland that was not harvested (primarily because it failed or was left idle) and crop infrastructure land. While this latter set of lands did not produce crops, it was nontheless part of the US cropland footprint.

Harvested lands for feed, fiber, and fuel were calculated as described below, then subtracted from total harvested cropland to obtain a preliminary estimate of the amount of land used to produce plant-based food directly consumed by humans. To determine the amount of non-harvested cropland and infrastructure land associated with each of these four categories of harvested crops, the area of harvested land in each category was divided by total harvested area to obtain the fraction of harvested land in each category. The fraction for each category was then multiplied by total nonharvested cropland and added to the harvested area for that category to obtain an estimate of the total area needed to produce feed, fiber, biofuels, and food. This approach was adopted to proportionally distribute non-harvested cropland and infrastructure land among the major categories, as complete data on the amount of infrastrure, fallow, and failed cropland belonging in each category were not available. Data for a fifth category of cropland, horticulture, was also obtained from the Ag Census (USDA 2014). As data for this category includes harvested and non-harvested land, the total area was subtracted from the remaining food land.

The area of cropland harvested for fiber was obtained directly from the Agricultural (Ag) Census (USDA 2014).

Land harvested for biofuels was obtained from USDA data on diversion of crops for ethanol and biodiesel production. Harvested area for ethanol production was determined by dividing bushels of corn diverted to fuel ethanol in 2012 (USDA 2018a) by corn yield estimates for that year (USDA 2018b). For soy, amounts diverted for fuel are reported in pounds of oil (USDA 2018a). Since oil makes up approximately 11 lb of every bushel (USDA 1988), pounds were divided by 11 to obtain total bushels. Since soybeans processed for biodiesel also yield economically valuable soybean meal (soy crush) used as feed, it was necessary to allocate a fraction of these bushels to each of these coproducts. This study follows Eshel *et al.* (2014)

in using an approximate economic and caloric fraction of 40% oil, 60% meal/crush. The number of bushels was multiplied by 0.4, then divided by average 2012 yields (USDA 2018c) to obtain total area.

Feed cropland was calculated from USDA data on bushels diverted for feed along with corresponding yield data. Areas of corn, sorghum, barley, and oats harvested for feed were calculated from the Feed Grain Yearbook for 2012 (USDA 2018b). The area of soy and soy crush used for feed was obtained from the Soy Yearbook for 2012 (USDA 2018c, soy crush bushels multiplied by 0.6, based on Eshel *et al.* 2014). Harvested area for wheat and rye feed were obtained from the Wheat Data Yearbook Tables (USDA 2018d). Lastly, area harvested for feed roughage (hay, haylage, grass silage, greenchop, corn silage, and sorghum silage) were obtained from the Ag Census (USDA 2014).

Grazing Land (Meat/Animal Production Land)

Meat production land consists of grazing land, livestock infrastructure land, and cropland for feed. Calculations for the latter two were described above. Grazing land exists on public and private lands as pasture (lands managed specifically for grazing) and rangelands (semi-natural areas not explicitly managed for grazing, but nonetheless modified by grazing from domestic livestock). Federal grazing land area was calculated from Bureau of Land Management rangeland area (USDI 2013) and U.S. Forest Service grazing allotments (USDA 2013). Private pastureland and rangeland area was obtained from the National Resource Inventory (USDA 2015).

RESULTS

Non-Biomass Developed Land

The total area of non-federal developed land in the conterminous US and Hawaii in 2012 was 459,375 km^2. Total developed land in Alaska came to 1,496 km^2. Developed land on federal military bases within the conterminous US covered 3,996 km^2. Combined this yields a total minimum area of developed land within the US of 464,867 km^2 (Table 1).

Table 1. Developed land by category.

Land Category	*Area (km^2)*
Industrial/Manufacturing	6,528
Commercial	14,510
Institutional/Government	9,886
Major Transportation	36,359
Residential	205,297
Outdoor Recreation & Resources	18,854
Water Use & Access	10,833
Conservation Land	7,276
SUBTOTAL: Non-Biomass Developed Land	*309,543*
Crop Infrastructure	53,532
Livestock Infrastructure	82,287
SUBTOTAL: Biomass Production Developed Land	*135,819*
SUBTOTAL: Unassigned Development	*19,505*
TOTAL DEVELOPED LAND	*464,867*

Results of partitioning developed land into more specific land use categories are presented in Table 1. After subtracting unassigned lands (19,505 km^2) and developed lands involving biomass production (135,819 km^2), total known non-biomass developed lands came to 309,543 km^2 (Table 1). Since most assigned developed land fell under the non-biomass category, for simplicity's sake, non-biomass and unassigned developed land are grouped together in subsequent discussions.

Biomass Production Land

Area of forest land significantly impacted by harvesting (Wood Production Land) was 375,649.8 km^2 (Oswalt *et al.* 2014) (Table 2).

Table 2. US domestic land footprint by major category.

Land Category	*Area (km^2)*	*% Contiguous US Land Area*
Wood Production Land	375,650	4.9
Cropland for Fuel	225,802	2.9
Cropland for Fiber	48,756	0.6
Cropland for Horticulture	2,880	0.0
SUBTOTAL: Fuel & Fiber Land	*653,088*	*8.5*
Meat/Animal Production Land	3,922,198	51.2
Cropland for Feed	695,064	9.1
Livestock Infrastructure	82,287	1.1
Private Pastureland	490,229	6.4
Private Rangeland	1,642,122	21.4
BLM Rangeland	628,044	8.2
FS Grazing Allotments	384,452	5.0
Cropland for Food	606,241	7.9
SUBTOTAL: Food Production Land	*4,528,439*	*59.1*
SUBTOTAL: Non-Biomass Developed Land (& Unassigned)	*329,048*	*4.3*
TOTAL LAND FOOTPRINT	*5,510,576*	*71.9*

Harvested cropland in 2012 was 1,274,618 km^2 (USDA 2014). Non-harvested cropland and infrastructure was 304,126 km^2 (250,594 km^2 other cropland – USDA 2014; 53,532 km^2 crop infrastructure – Table 1).

Harvested fiber land came to 39,363.9 km^2. This represents 3.1% of total harvested area. Multiplying this number expressed as a fraction by total non-harvested cropland puts its portion of this land at 9,392.3 km^2, bringing total fiber cropland & infrastructure to 48,756.2 km^2 (Table 2).

The total area of harvested biofuel land came to 182,304.1 km^2, or 14.3% of all harvested land. Using this to calculate its fraction of non-harvested land brings its share of the latter to 43,498.0 km^2. Thus, total biofuel production area came to 225,802.1 km^2 (Table 2).

Horticultural lands consisted of 1,252 km^2 of Christmas tree plantations, 1,300.3 km^2 for sod, and 328 km^2 floriculture/seed lands (USDA 2014), totaling 2,880.2 km^2 (Table 2).

Grazing lands were comprised of 490,228.5 km^2 of private pastureland (USDA 2015), 1,642,122.3 km^2 of private rangeland (USDA 2015), 628,044.0 km^2 BLM rangeland (USDI 2013), and 384,451.7 km^2 forest service grazing land (USDA 2013) (Table 2). Harvested feed cropland consists of 561,168.2 km^2, or 44.0% of harvested cropland. Adding its fraction of non-harvested crop and infrastructure land to this, total area for feed was 695,063.7 km^2 (Table 2). Combining these numbers with livestock infrastructure land, the total area of meat/animal production came to 3,922,198 km^2 (Table 2).

Subtracting harvested fiber, feed, and fuel land from total harvested cropland yielded a difference of 491,781.4, or 38.6% of harvested cropland. Combined with the remaining non-harvested area, a total of 609,121.2 km^2 is attributable to food and horticulture. Subtracting the horticulture total leaves 606,241.0 km^2 for food (Table 2).

DISCUSSION

These results reveal that the minimum, conservative estimate of the United States' domestic land footprint is 5,510,576 km^2 (Table 2). To put this in perspective, it is equivalent to nearly 72% of contiguous US land area (the lower 48 states, excluding Alaska and Hawaii) (Table 2). Note that this does not include large amounts of land impacted by American activities at home and abroad, including land submerged by hydroelectric dams, land burned from human-caused fires, large tracts of unnatural planted forests (akin to cropland), all land used outside the US to produce and transport imported products (including imported meat), roughly 800 foreign military bases (some the size of small cities – Vine 2015), the United States' fraction of land used for tourism abroad, land degraded by habitat fragmentation, and so on. The only set of data that is likely overestimated here is land identified as "cropland for food." Any land used for crop production that was not accounted for by domestic consumption for feed, fuel, fiber, or horticulture was placed in this category. Since the US was a net exporter of primary agricultural products in 2012 (USDA 2019), this includes land used to generate those net exports. However, it is unlikely this land area exceeds the large amounts of land that could not be accounted for in these analyses, such as those described above. Therefore, these results are likely an underestimate.

To understand how the United States' domestic land footprint fits within a global context, it helps to examine what the total human land footprint would be if everyone on Earth lived like the average American. To do this one must first calculate the per capita US footprint in 2012. According to the US Census Bureau, the mid-year population of the country in 2012 was approximately 313,914,040 people (US Census Bureau 2013). Dividing the total domestic land footprint by this value yields a per capita US footprint of 0.018 km^2, or 4.34 acres. Without any other context this figure may seem small. Setting aside the fact that this is likely an underestimate, one can provide that context by estimating the global land footprint if everyone on the planet needed 0.018 km^2, on average. The world population mid-2019 was approximately 7.7 billion (United Nations 2019). If the average global citizen in 2019 lived like the average American, the total global footprint would exceed 135 million km^2. This is more than all ice-free land on the entire planet (130.1 million km^2 – Hooke *et al.* 2012). In other words, if the rest of the world lived like people in the US, there would be no bioproductive wild lands left anywhere on Earth, and the current extinction and biodiversity crisis would be vastly worse. In short, the US land footprint grossly exceeds what would be proportional or sustainable.

Fortunately, most of the global population does not live like the average American, and all ice-free lands are not modified by humans. This is not to say that the current situation is acceptable. As of more than a decade ago, 53% of ice-free lands had been modified for human use (Hooke *et al.* 2012) and 75% of all global land showed a measurable human impact (Venter *et al.* 2016). As the global human population has grown significantly since then, the current global land footprint is almost certainly larger. To make matters worse, within the next three decades, the US population is projected to grow to 398 million (US Census Bureau 2018) and the global population is expected to reach 9.5 billion (United Nations 2019), nearly two billion more than the current population. Every net additional person added to the population requires more land. Given over a quarter of all species are currently threatened with extinction, due largely to habitat loss (IUCN 2020; Venter *et al.* 2006; Pereira *et al.* 2012), continued habitat destruction to meet the needs of two billion more people will greatly exacerbate the situation. Since the US contributes disproportionately to ecosystem losses, it is essential that Americans identify ways to significantly reduce their footprint.

While there are many actions that can and should be carried out to accomplish this, the findings of this study show that a single change alone could eliminate the majority of the US land footprint: drastically reducing farmed meat consumption (and other animal products). Meat/animal production land accounts for nearly three quarters (71%) of the total US land footprint, an area equivalent to 51% of the entire contiguous US. That is an extraordinarily heavy environmental burden, and one that could be largely eliminated if alternative protein sources were utilized. It is often assumed that meat is an essential component of the diet because, unlike most plants, it is rich in protein. One might further assume that if people eliminate meat from their diet, they'd either have protein deficient diets, or have to replace it with large amounts of plant-based protein, which in turn would require large amounts of land. Not so. When compared to protein rich crops like soy and peanuts, animals require substantially greater amounts of land to produce the same amount of protein. Beef is the worst in this regard. It takes approximately 140 times more land to produce the same amount of protein as plant-based protein sources such as tofu (Alexander *et al.* 2017). Similar results hold when comparing land needed to produce the same number of calories compared to a variety of plant products (Eshel *et al.* 2014; Alexander *et al.* 2017). Not only can substituting plant-based protein in place of beef save land, it can also significantly reduce other environmental impacts such as greenhouse gas emissions and improves the nutritional profile of a diet as well (Eshel *et al.* 2014, 2016). Other meat sources such as pork and chicken are not quite as land-intensive as beef due to the extensive use of highly concentrated factory farming (which has its own set of ethical and environmental problems – Henning 2011), but even they require roughly 4-14 times more land to produce the same amount of protein as plant-based alternatives (Alexander *et al.* 2017).

Based on figures in Table 2, if one assigns all 3,144,847 km^2 of grazing land to beef (at least 620,000 km^2 of which are suitable for crops – Eshel *et al.* 2014) and all cropland for feed to the most land-efficient of the other meats (requiring only 4 times as much land as vegetable protein), the elimination of animal production land and replacement of meat with vegetable protein could eliminate over 2/3 of the total US domestic land footprint (at least 3.7 million km^2). Even if one accepts that some animal production would remain for food, labor, recreation, entertainment, *etc.*, a large-scale replacement of meat with plant-based protein could still eliminate well over half the US domestic land footprint. No other action or combination of actions, can come even close to this impact.

One common objection to the large land burden of meat is that many grazing lands are semi-natural and therefore not as heavily modified as cropland and developed land. While this may be partly true, livestock nonetheless profoundly alter many of these ecosystems, causing particularly heavy damage to riparian and stream ecosystems, contributing to soil erosion and desertification, altering species compositions, reducing primary productivity, and a host of other deleterious impacts (Fleischner 1994; Belsky *et al.* 1999; Krausman *et al.* 2009). Nevertheless, for the sake of argument it is possible to provide a more conservative, best case scenario of the impact of meat production. For this revised calculation, only the following will be included: cropland for feed (695,064 km^2 – Table 2), livestock infrastructure land (82,287 km^2 – Table 2), Bureau of Land Management (BLM) land that has been evaluated by BLM staff and found to significantly degraded by livestock (147,829 km^2 – USDI 2013), and grazing on prime, bioproductive land capable of supporting crops, forests, or other mature ecosystems that would be incompatible with grazing (620,000 km^2 – Eshel *et al.* 2014). The new total of land significantly impacted by animal production comes to 1,545,180 km^2. Despite the fact that this is a gross underestimate of livestock's footprint, it still nearly equals all other parts of the US domestic land footprint combined (1,588,377 km^2). Thus, no matter how one calculates it, meat/animal production comprises a massive and largely unnecessary part of the footprint.

Another set of concerns one might raise regarding these findings relates to the practicality of significantly reducing meat consumption in the US, and the likely fate of any lands abandoned from animal production. People who consume meat are unlikely to cease or reduce this consumption without compelling reasons to do so. The data presented here should be seen as simply one of the first steps in this process by providing those concerned about the environment with one more compelling reason to decrease consumption of these products. How this can be done is as simple as replacing all or a portion of the meat in one's diet with protein rich vegetarian alternatives, including legumes or a growing array of vegetarian "meats" available in grocery stores and restaurants. As for the fate of lands no longer needed for animal production, this will likely depend on ownership and market conditions. Many animal production lands are on government property. Removing animal production from these lands would certainly reduce human impact on these lands, and in many cases allow for the restoration of natural conditions. Where native herbivores and their predators have been removed or displaced to accommodate livestock, the return of these species would help further the return to native conditions. As for private animal production lands, much depends on the desires and resources of land owners as well as land use demands in the region. In some cases, these lands would return to natural conditions, much as the abandonment of agricultural lands in the northeastern US led to forest regrowth there. Purchasing of some of these lands by governmental or non-governmental conservation organizations, or offering tax incentives or other financial incentives for conservation easements would certainly help increase the probability that these lands will return to natural conditions. In other areas were development is increasing to accommodate a growing population, some of these lands may be replaced with development. An important point to note is that, while this study is very much about reducing America's land footprint, a less ambitious goal would simply be to slow the rate of increase in this footprint. Thus, even if some reductions in animal productions lands are replaced with development (or another human land use), those reductions still yielded important benefits by ensuring existing native habitats such as forest, grasslands, wetlands, etc. did not have to be destroyed to meet the growing demands for land to accommodate a growing human population.

All of the above is not to say that reducing meat/animal production should be the only focus for decreasing the US land footprint. It is merely the single best and most significant way of doing so. Ideally, Americans should examine all land-intensive activities/products and choose alternatives that are less land-intensive or exert less pressure on native ecosystems. For example, many areas in the US and abroad are experiencing rapid growth of poorly planned urban sprawl (Artmann *et al.* 2019). Urban sprawl leads to more rapid habitat loss and fragmentation compared to compact, green cities (Artmann *et al.* 2019). As urbanization is expected to grow significantly in the coming decades, posing increased threats to biodiversity (McDonald *et al.* 2008), pushing municipalities and other governmental bodies to embrace smart, compact, green growth could help lessen the environmental toll.

Another area of concern is the continued growth of allegedly "green" forms of food and energy production that actually require more land than standard modes of production. A prime example of this is conventional biofuels (corn ethanol and soy biodiesel). These fuels, which use the equivalent of nearly 3% of contiguous US land area, are extremely destructive, requiring up to *1000 times more land* per unit of energy generated than nuclear power, and dozens of times more than fossil fuels (Brook & Bradshaw 2014). They have also been found to drive up food prices, contribute to food shortages, and increase other environmental problems such as water pollution (Pimentel *et al.* 2009). Since fossil fuels are typically used at every stage of their production, these biofuels often do very little to actually reduce overall carbon emissions (Djomo & Ceulemans 2012). Their continued expansion would lead to massive habitat loss, exacerbating the ongoing biodiversity crisis, and actually result in a net increase in carbon emissions in some cases (Groom *et al.* 2008; McDonald *et al.* 2009; Djomo & Ceulemans 2012; Webb & Coates 2012). While food waste and algae-based biofuels have an extremely low footprint and should be promoted (Groom *et al.* 2008), conventional biofuels (those used in the US) have an unacceptably high environmental burden and should be eliminated from the US energy mix.

Other renewables too can have considerably higher land footprints if not sited properly. Solar, when placed in arrays requiring removal of habitat or cropland, rather than over existing infrastructure, or wind turbines, when not placed offshore or over existing human modified landscapes, can also destroy significantly more habitat than conventional energy sources like nuclear (Brook & Bradshaw 2014).

A similar situation applies to food production. Cropland for food is the second largest individual category of land use in the US after meat/animal production (Table 2). Choices consumers make with respect to non-meat food sources can have significant impacts on their land footprint. When it comes to foods touted as "sustainable," there is tremendous variability in the extent to which they live up to that moniker. Things such as vertical and community gardening placed in existing developed landscapes offer the potential to increase food production with very minimal to no increase in land footprint. These modes of production should be encouraged. By contrast, organic agriculture is much more problematic. On average, organic crops have significantly lower yields than conventional crops (Seufert *et al.* 2012; Kravchenko *et al.* 2017). Combined with the additional land typically needed to produce fertilizer (from plant or livestock sources), organic agriculture often requires 1.5-2 times as much land as conventional agriculture to produce the same amount of food (Kirchmann *et al.* 2008; Kravchenko *et al.* 2017). There are exceptions, however. Yields for many organic fruits can rival that of conventional modes of production (Seufert *et al.* 2012). Where organic crops can achieve sustained yields at the levels seen in conventional crops, using fertilizers that require little additional land, such as human waste, organic can offer an excellent alternative to conventional agriculture. Unfortunately, this is not the case for most organic systems at present. Until this changes, it is not practical or sustainable to implement organic agriculture on a large scale. It is not feasible to feed the existing 7.7 billion people on the planet (800 million of which are malnourished – FAO *et al.* 2018), along with another 3 billion people projected by the end of the century (United Nations 2019), using agricultural techniques that require significantly more land. Instead, scientific and technological advances that increase yields while reducing pesticide application (*e.g.*, integrated pest management), nutrient runoff, and land footprint, regardless of arbitrary labels, should be promoted.

Finally, projected population growth should not be viewed as a *fait acompli*. Every additional person added to the planet adds to the overall human footprint. For too long, many environmentalists have avoided addressing the serious problem of population growth. National and global land footprints are already too large, as evidenced by the tremendous number of species threatened with extinction due to habitat loss (Venter *et al.* 2006; Vie *et al.* 2009; Pereira *et al.* 2012; Tittensor *et al* 2014; Grooten & Almond 2018). Increasing these footprints to accommodate more than 3 billion additional people will be devastating. Aside from reducing meat consumption, there is perhaps no other change humans could make that would have a greater impact on habitat loss and biodiversity declines in the future than ending the continued expansion of the human population.

ACKNOWLEDGEMENTS

I would like to thank Jeremy Gencavage, Logan Hall, and Erin Silva of the Eastern Shore Regional GIS Cooperative and especially Art Lembo at Salisbury University for their tremendous assistance in cross-tabulating the NLUD and NLCD data in ArcGIS. I am also grateful to Sonja Oswalt of the US Forest Service for helping obtain timber harvest data.

REFERENCES

Aide, T.M., Zimmerman, J.K., Pascarella, J.B., Rivera, L., & Marcano-Vega, H. (2001) Forest regeneration in a chronosequence of tropical abandoned pastures: Implications for restoration ecology. *Restoration Ecology* 8: 328-338.

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., & Rounsevell, M.D. (2017) Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security* 15: 22-32.

Artmann, M., Kohler, M. Meinel, G., Gan, J., & Ioja, I-C. (2019) How smart growth and green infrastructure can mutually support each other — A conceptual framework for compact and green cities. *Ecological Indicators* 96: 10-20.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., *et al.* (2011) Has the Earth's sixth mass extinction already arrived? *Nature* 471: 51–57.

Belsky, A.J., Matzke, A., & Uselman, S. (1999) Survey of livestock influences on stream and riparian ecosystems in the western United States. *Journal of Soil and Water Conservation* 54: 419-431.

Bradshaw, C.J.A., Giam, X., & Sodhi, N.S. (2010) Evaluating the relative environmental impact of countries. *PLoS ONE* 5: e10440.

Brook, B.W., & Bradshaw, J.A. (2014) Key role for nuclear energy in global biodiversity conservation. *Conservation Biology* 29: 702-712.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M. *et al.* (2010) Global biodiversity: Indicators of recent declines. *Science* 328: 1164-1168.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper D.U., Perrings, C., Venail1, P., Narwani, A., *et al.* (2012) Biodiversity loss and its impact on humanity. *Nature* 486: 59-67.

Ceballos, G., Ehrlich, P.R., & Dirzo, R. (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *PNAS* 114: E6089-E6096.

d'Amour, C.B, Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K-H., Haberl, H., *et al.* (2017) Future urban land expansion and implications for global croplands. *PNAS* 114: 8939-8944.

Dirzo, R., & Raven, P.H. (2003) Global state of biodiversity and loss. *Annual Review of Environment Resources* 28: 137–167.

Djomo, S.K., & Ceulemans, R. (2012) A comparative analysis of the carbon intensity of biofuels caused by land use changes. *GCB Bioenergy* 4: 392-407.

Dunn, R.R. (2004) Recovery of faunal communities during tropical forest regeneration. *Conservation Biology* 18: 302-309.

Eshel, G., Shepon, A., Makov, T., & Milo, R. (2014) Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *PNAS* 111: 11996-12001.

Eshel, G., Shepon, A., Noor, E., & Milo, R. (2016) Environmentally Optimal, Nutritionally Aware Beef Replacement Plant-Based Diets. *Environmental Science & Technology* 50: 8164-8168.

FAO, IFAD, UNICEF, WFP & WHO (2018) *The State of Food Security and Nutrition in the World 2018.* Rome: FAO.

Fleischner, T.L. (1994) Ecological costs of livestock grazing in western North America. *Conservation Biology* 8: 629–644.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., & Foley, J.A. (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *PNAS* 107: 16732-16737.

Groom, M.J., Gray, E.M., & Townsend, P.A. (2008) Biofuels and biodiversity: Principles for creating better policies for biofuel production. *Conservation Biology* 22: 602-609.

Grooten, M., & Almond, R.E.A. (Eds) (2018) *Living Planet Report - 2018: Aiming Higher*. Gland, Switzerland: WWF.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., *et al.* (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* 342: 850-853.

Henning, B.G. (2011) Standing in livestock's 'long shadow': The ethics of eating meat on a small planet. *Ethics & the Environment* 16: 63-93.

Hoffmann, M., Hilton-Taylor, C., Angulo, A., Böhm, M., Brooks, T.M., Butchart, S.H.M., Carpenter, K.E., *et al.* (2010) The Impact of conservation on the status of the World's vertebrates. *Science* 330: 1503-1509.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., *et al.* (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing* 81: 345-354.

Hooke, R.L.B., Martín-Duque, J.F., & Pedraza, J. (2012) Land transformation by humans: A review. *GSA Today* 22: 4-10.

Hooper, D.U., Adair, E.C., Cardinale, B.J., Byrnes, J.E.K., Hungate, B.A., Matulich, K.L., Gonzalez, A., *et al.* (2012) A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* 486: 105-109.

IUCN (2020) *The IUCN Red List of Threatened Species. Version 2020-1* [www document]. URL http://www.iucnredlist.org

Kirchmann, H., Bergstrom, L., Katterer, T., Andren, O., & Andersson, R. (2008) Can organic crop production feed the world? In: *Organic Crop Production – Ambitions and Limitations,* eds. Kirchmann, H., Bergstrom, & L. Dordrecht, pp. 39-72. The Netherlands: Springer.

Kravchenko, A.N., Snapp, S.S., & Robertson, G.P. (2017) Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. *PNAS* 114:926-931.

Krausman, P.R., Naugle, D.E., Frisina, M.R., Northrup, R., Bleich, V.C., Block, W.M., Wallace, M.C., *et al.* (2009) Livestock grazing, wildlife habitat, and rangeland values. *Rangelands* 31:15-19.

Leakey, R. & Lewin, R. (1992) *The Sixth Extinction: Patterns of Life and the Future of Humankind*. New York, NY: Doubleday.

Maxwell, S.L., Fuller, R.A., Brooks, T.M., & Watson, J.E.M. (2016) The ravages of guns, nets and bulldozers. *Nature* 536: 143-145.

McDonald, R.I., Kareiva, P., & Forman, R.T. (2008) The implications of current and future urbanization for global protected areas and biodiversity conservation. *Biological Conservation* 141: 1695-1703.

McDonald, R.I., Fargione, J., Kiesecker, J., Miller, W.M., & Powell, J. (2009) Energy sprawl or energy efficiency: Climate policy impacts on natural habitat for the United States of America. *PLoS ONE* 4: e6802.

Meli, P., Holl, K.D., Benayas, J.M.R., Jones, H.P., Jones, P.C., Montoya, D., & Mateos, D.M. (2017) A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. *PLoS ONE* 12: e0171368.

Pereira, H.M., Navarro, L.M., & Martins, I.S. (2012) Global biodiversity change: The bad, the good, and the unknown. *The Annual Review of Environment and Resources* 37: 25-50.

Pimentel, D., Marklein, A., Toth, M.A., Karpoff, M.N., Paul, G.S., McCormack, R., Kyriazis, J., *et al.* (2009) Food versus biofuels: Environmental and economic costs. *Human Ecology* 37: 1-12.

Oswalt, S.N., Smith, W.B., Miles, P.D., & Pugh, S.A. (2014) *Forest Resources of the United States, 2012: A Technical Document Supporting the Forest Service 2015 Update of the RPA Assessment*. Washington, DC: United States Department of Agriculture, Forest Service.

Seufert, V., Ramankutty, N., & Foley, J. (2012) Comparing the yields of organic and conventional agriculture. *Nature* 485:229-232.

Simas, M., Pauliuk, S., Wood, R., Hertwich, E.G., & Stadler, K. (2017) Correlation between production and consumption-based environmental indicators. *Environmental Indicators* 76: 317-323.

Theobald, D.M. (2014) Development and application of a comprehensive land use classification and map for the US. *PloS ONE* 9: e94628.

Tittensor, D.P., Walpole, M., Hill, S.L.L., Boyce, D.G., Britton, G.L., Burgess, N.L., Butchart, S.H.M., *et al.* (2014) A mid-term analysis of progress toward international biodiversity targets. *Science* 346: 241-244.

United Nations (2019). *World Population Prospects 2019: Highlights* (ST/ESA/SER.A/423). New York, NY: United Nations, Department of Economic and Social Affairs, Population Division.

US Census Bureau (2013) *Annual Estimates of the Resident Population for Selected Age Groups by Sex for the United States, States, Counties, and Puerto Rico Commonwealth and Municipios: April 1, 2010 to July 1, 2012.* [www document]. URL https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk

US Census Bureau (2018) *International Programs | International Data base | Version: 12.03.21.* [www document]. URL https://www.census.gov/data-tools/demo/idb/informationGateway.php

US Census Bureau (2019) *U.S. Trade in Goods and Services - Balance of Payments (BOP) Basis* [www document]. URL https://www.census.gov/foreign-trade/statistics/historical/gands.pdf

USDA (1988) *The Soybean Industry. Agricultural Economic Report No. 588.* Washington, DC: United States Department of Agriculture, Forest Service.

USDA (2013) *Grazing Statistical Summary, FY2012*. Washington, DC: United States Department of Agriculture, Forest Service.

USDA (2014) *2012 Census of Agriculture, United States, Summary and State Data.* Washington, DC: United States Department of Agriculture, National Agricultural Statistics Service.

USDA (2015) *2012 National Resources Inventory, Summary Report*. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service.

USDA (2018a) *U.S. Bioenergy Statistics*. Washington, DC: United States Department of Agriculture, Economic Research Service [www document]. URL https://www.ers.usda.gov/data-products/us-bioenergy-statistics/

USDA (2018b) *Feed Grain Yearbook for 2012*. Washington, DC: United States Department of Agriculture, Economic Research Service [www document]. URL https://www.ers.usda.gov/webdocs/DataFiles/50048/Feed%20Grains%20Yearbook%20Tables-All%20Years.xls?v=43298

USDA (2018c) *Soy Yearbook for 2012*. Washington, DC: United States Department of Agriculture, Economic Research Service [www document]. URL https://www.ers.usda.gov/webdocs/DataFiles/52218/Soy.xlsx?v=43189

USDA (2018d) *Wheat Data: Yearbook Tables.* Washington, DC: United States Department of Agriculture, Economic Research Service [www document]. URL www.ers.usda.gov/webdocs/DataFiles/54282/Wheat%20Data-All%20Years.xls?v=43294

USDA (2019) *U.S. trade surplus smallest since 2007.* Washington, DC: United States Department of Agriculture, Economic Research Service [www document]. URL https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58310

USDI (2013) *Fiscal Year 2012 Rangeland Inventory, Monitoring, and Evaluation Report.* Washington, DC: United States Department of Interior, Bureau of Land Management.

Venter, O., Brodeur, N.N., Nemiroff, L., et al. (2006) Threats to endangered species in Canada. *BioScience* 56: 903-910.

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., *et al.* (2016) Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications* 7: 12558.

Vié, J.-C., Hilton-Taylor, C., & Stuart, S.N. (2009). *Wildlife in a Changing World An Analysis of the 2008 IUCN Red List of Threatened Species*. Gland, Switzerland: IUCN.

Vine, D. (2015) *Base Nation: How U.S. Military Bases Abroad Harm America and the World.* New York, NY: Metropolitan Books.

Webb, A., & Coates, D. (2012) *Biofuels and Biodiversity.* Montreal: Secretariat of the Convention on Biological Diversity.

BIO

Aaron Hogue received his PhD in biology at Northwestern University. He subsequently went on to complete a postdoctoral fellowship at Duke University School of Medicine, Department of Biological Anthropology and Anatomy, prior to arriving at Salisbury University, where he is now an associate professor in the Department of Biological Sciences. His research broadly examines the relationship between organisms (particularly mammals) and their environment, with an increasing focus on the impact of our own species on terrestrial ecosystems and the species they contain.

Approaches to Fostering Industry-Academic Collaboration

Joanne M. Horn

J. Horn Bioservices LLC

Abstract

Civil societies today face enormous pressures associated with shrinking resources relative to continuing population growth and climate change. In response to these challenges governments and industry can more effectively fund programs to foster directed and impactful collaborations between the academic and industrial sectors. The downstream benefits of these collaborations include reducing research costs, better use of university research infrastructure, retaining student talent for future employment, training students in real-world industrial problem-solving, taking advantage of academic networks, and blue-sky approaches. While individual States have sponsored these programs, and have been shown to generate far more revenues than costs, Federal programs can be implemented that would have far-reaching effects. Grants, Grand Challenges, small business incentives, contract set-asides, and fellowship programs are some of the programs that can be executed on the national level to achieve these ends.

Rationale and Need

SUCCESSFUL COLLABORATIVE INDUSTRY-UNIVERSITY research models have been shown to have very significant impacts on regional economies. Virtually all technology hubs in the U.S. are co-located and partly driven by cooperative work with large research universities (*e.g.*, Boston, MA; Research Triangle, NC; San Francisco, CA; San Diego, CA). Leveraging the cutting-edge knowledge, imagination, and reasonable research costs at partner universities have propelled industries forward, thus creating capital gains. At the same time these partnerships have created a pipeline of trained students and academics for downstream employment, opened up new fields of knowledge, and allowed universities to broaden their programs and facilities. Academic collaborations not only drive workforce development, but incentivize students to stay local, thus retaining talent while also attracting new businesses to the area. Thus, partnerships between universities and industry can be extremely mutually beneficial. Clearly, these types of partnerships have had far-reaching economic and educational benefits, and further enhances the social mission of universities.

Expanding and capitalizing on these collaborations requires an understanding of how they are initiated. In Maryland there are a number of organizations that work with academia-industry partnerships, however most focus solely on Technology Transfer, a limited option. While large corporations may undertake a focused study to determine the best institutions with which to partner, the truth is that most partnerships develop *ad hoc*: For example individual researchers know each other through professional meetings or publications, a Board Member is an alumnus, a Dean knows someone doing complimentary work at a particular company, or a company's desire to support a local institution. And while personal relationships and public support are always important, they are not always the most effective means of seeking out the best partners. Also, much of our current economy is being driven by small business and startups which have few resources to initiate grants or capital funds to universities, but arguably may benefit the most from having these collaborations. In short there is no set formula for finding partners, funding, or threading one's way through negotiations, particularly for small companies.

Potential Federal Models

So what approaches can government use to incentivize the most productive collaborations between industry and academia? The following examples provide some approaches:

1. Grants to Public Universities for collaborative projects with industry; industry finances matching funding

This is a model that was very successful in California when the State funded $450M ($20M/year) from 1996 to 2007 to Univ. California researchers to collaborate with industry on projects strategically aimed at benefiting the California economy. The focus was on early stage basic feasibility work. It resulted in supporting over 2000 graduate students, allowed companies to undertake projects they could not perform in-house, created 5000 jobs, helped startups raise new capital, encouraged faculty to expand their collaborations with other companies, and resulted in some students starting their own firms[1].

Maryland instituted a similar program called the Maryland Industrial Partnerships (MIPS), except that the focus was on translational research, explicitly solving critical problems in product development (so farther downstream than the UC approach). MIPS has been in place for 30 years with about $1.5M invested per year ($51M over the lifetime of the program) with a $100K limit per project. It has more than paid for itself, generating $166M per year in income and other taxes from the jobs and products generated[2].

These programs have been hugely successful and generated much more value than they have cost. Therefore, it seems wise to expand these types of programs to the Federal level. Other components to them might include a mandatory requirement for educating high school interns, or incorporating bachelor students into the projects, along with graduate students and post-doctoral fellows. The programs might be likewise broadened by incorporating other disciplines, including business or marketing, design or law to make them multi-disciplinary, reflecting true business needs.

2. *Financing Institutes that Address Grand Challenges*

Federal agencies have traditionally funded large independent research institutes or projects within Universities, including the DOE national labs, DoD labs (e.g., Lincoln Lab at MIT), and NSF labs and study centers. None of these institutions, however, has a direct mandate to intentionally and foundationally involve industries, nor are any directly aimed at propelling economic development. There have been industries that banded together to establish institutes, for example GSK, Merck, and Novartis started the Structural Genomics Consortium to carry out basic research; all results are placed in the public domain so there are no IP issues. Grand Challenges attack critical problems across broad areas, result in transformational change, and create new fields and markets. The Federal government could

---

[1] Edmonson, G., Valigra, L., Kenward, M., Hudson, R.L. and Belfield, H. 1999. Making Industry-University Partnerships Work, Science|Business Innovation Board AISBL, 50 pp.

[2] http://www.mips.umd.edu/impact.html

create Grand Challenge-based institutes that demand the incorporation of both industries and academia. This would have broad appeal to both sectors; academia thrives on long term problem- solving, while industries need the basic questions to be addressed in the context of relevant markets. The Institutional funding could be based on urgent issues facing the Nation and our economy, *e.g.*, energy distribution, fisheries restoration, advanced transportation technologies, global health security, agricultural adaptation to climate and globalism, CO_2 sequestration and mitigation, novel infrastructure materials. Moreover, these institutes could transcend traditional academic and governmental silos, incorporating science, manufacturing, business, law, and policy to address these problems with a systems approach.

3. Startup- or small business- focused grants that incentivize working with academics

Small Business Innovative Research (SBIR) programs do not typically demand any specific partnering, but some set-aside of those grant funds could be used to foster collaborations between academia and industry. Especially for small firms with limited resources these collaborations could prove a pivotal element to their success. An alternative approach could be to set aside some of the SBIR funding to work with Federal Labs; this would avoid the dilemma that Federal labs often encounter to collaborate: sacrificing their own operating funds to support a small business collaboration.

4. Government contract research set-asides for industries to work with universities

Federal agencies often contract large research-directed companies (CROs, Contract Research Organizations) to carry out sizable, early stage projects. If contract vehicles included a requirement to work with universities, it would foster collaborations. This would be particularly amenable for executing early stage ideas, feasibility studies, or technology integration. Large government contractors could manage their own competitive proposal process to work with universities on a given contract. The academic component could be managed as a subcontract to the primary contractor such that the FAR requirements could be handled by the prime contractor. Accountability could be built into the reporting metrics including, number of students taught, employees placed, Intellectual property generated, *etc.*

5. Fellowship program to work as part of the graduate degree

The Federal government has trainee fellowships for institutions that fund graduate students throughout their graduate school career; these are highly competitive programs that typically fund an entire department of graduate students. There are also specific niche programs that focus on minority fellowships, or other targeted sub-populations. However, to our knowledge, there are no programs that encourage students (and by extension, their mentors and graduate departments) to spend a semester working within industry. This affords a chance for both the student and the company to gauge experience and performance, and it sets the stage for generating a pipeline of trained employees. The student gets to work on applied problems, in real teams, and function in a corporate environment with real-world constraints. This type of program would also encourage faculty to engage with industry, which could generate larger downstream collaborations. With fewer than 20% of Ph.D. students able to secure academic positions[3], this shows students what they can expect in industry.

Summary

The Nation and the world face enormous challenges to meet the needs of population reaching 9.7 billion people by 2050[4], along with changing climate, aging infrastructure, income disparity, and resource constraints. All challenges, however, also present opportunities to meet these needs with creative solutions that generate economic value. Combining the benefits of industry and academic research generates an engine, using the blue-sky visions of academic license with the market-driven guardrails of industry. These combinations have been shown to be a huge driver of creative solutions and wealth. The U.S. government should encourage these relationships and guide their formation.

---

[3] https://lifesciencenetwork11.connectedcommunity.org/blogs/leah-cannon/2016/09/15/how-many-phd-graduates-become-professors

[4] www.un.org/en/development/desa/news/population/2015-report.html

Bio

Joanne Horn received a Ph.D. from Univ. California Berkeley in microbiology, where she studied DNA repair and recombination in *Pseudomonas*. Dr. Horn spent a post-doctoral fellowship at the German Natl. Institute for Biotechnology, working on generating bacterial metabolic pathways for mercury decontamination, and enzymatic fusion proteins. Following her studies Horn taught at Univ. West Florida, then went worked at Lawrence Livermore Natl. Laboratory, followed by research and development in the commercial biotechnology sector. Horn has supervised global health security projects in Central Asia and Africa as part of a US Government Defense contract, and directed a State-funded nonprofit aimed at driving STEM-based industries by partnering with higher education. She is currently an independent consultant.

RESOLVING THE KICKER'S CONUNDRUM AND THE PUNTER'S PARADOX

A physics-based equation to rank football kick(ers) and punt(er)s

T. C. Lipscombe

Catholic University of America

Abstract

In American football kickers attempt to maximize both the distance travelled by the ball and the hang time. These two objectives, though, are mutually exclusive, and result in the kicker's conundrum or the punter's paradox: what should the kicker aim for? By means of a simple football observation we develop a simple expression for the optimal kick in football. In real life, though, the ideal punt is not likely to happen. Kicking camps, which young college prospects attend to catch the attention of coaches, rate kickoffs and punts in terms of a points system based on a simple formula. This we show leads to a different criterion, which rewards "Bigfoot" – the player who can kicker the hardest – over the perfect punter. Young kickers attending the camp should adopt a different strategy, kick according to the equation, and kick as hard as possible. We propose an alternative formula, one that rewards range and hang time, but which punishes violations of the "perfect punt" condition. College coaches on the lookout for kicking and punting talent might want to think again about the rankings generated by such kicking camps.

Introduction

THE EQUATIONS FOR PROJECTILE MOTION are well known. These predict that a ball, launched at an angle θ to the horizontal at a speed v, will land at a distance (the range) R, given by Equation (1):

$$R = \frac{v^2 \sin 2\theta}{g}. \tag{1}$$

This holds when the launch and landing heights are equal, which truly requires a level playing field. The maximum range, then, occurs when the launch angle is 45°.

The ball's time of flight (or hang time), T, is determined by equation (2):

$$T = \frac{2v\sin\theta}{g}. \qquad (2)$$

This is maximum when the ball is kicked vertically upwards, at an angle of 90°.

These equations illustrate the kicker's conundrum or the punter's paradox: The football coach who selects the team and makes the cuts wants both distance *and* hang time on the kickoffs and punts — but physics dictates that you can't have both[1]. Above the 45° launch angle, hang time increases but range decreases. Below 45°, the range will decrease *and* the time of flight will decrease. Those who have watched young kickers in action know full well they tend to kick the ball at a relatively low angle, assuming this will give them maximum range. It doesn't — and furthermore, it ruins their hang time.

To resolve the kicker's conundrum, we appeal to football. Namely, no matter how far you kick the ball, no matter how long it hangs in the air, the coach also wants the receiving team to be unable to return the kick off or punt. Consider, then, a kickoff. Players on the kicking team (the kick-off coverage) are sprinting at full speed and, optimally, cross the line from which the ball is being kicked (the 40-yard line in high school; the 35-yard line in college; the 25-yard line in the NFL) at the exact moment when the ball is struck. If they are ahead of that line at the moment of impact, they are offside. If they are behind that line, they cannot run as far down the field as they could before the ball is caught by the receiving team.

This ideal kickoff resolves the problem once we assume that the kicking team all sprint at speed u. Namely, we want the ball to land at exactly the moment when the kicker's team arrives. However, the downfield component of the ball's velocity is $v\cos\theta$. The perfect punt or the ideal kick, then, is one whose launch angle is determined by Equation (3):

$$u = v\cos\theta. \qquad (3)$$

---

[1] The kicker's dilemma, as it was called, was probably first introduced into physics in Peter Brancazio "The Physics of Kicking a Football", *The Physics Teacher*, October 1985, 403–407. He used data from NFL kickers to explore their launch parameters of angle and velocity.

This simple expression is part of a larger body of work — pursuit curves.[2] In essence, we are looking at the pursuit of a parabolic projectile (the ball) by a pursuer who moves in a straight line at constant speed.

Typical of a pursuit curve, we introduce the velocity of the ball relative to that of the runner. Namely, define α by Equation (4):

$$\alpha = \frac{v}{u}. \tag{4}$$

Immediately, we know that $\alpha \geq 1$. Otherwise, the ball would always lag behind the runner. Note also that $\cos\theta = \frac{1}{\alpha}$. This suggests that the faster the ball is launched, the higher the launch angle can be to allow the kick coverage to chase it down optimally.

We can calculate the range and the hang time of such a kick off. We know from Equation (3) that $\sin\theta$ is given by Equation (5):

$$\sin\theta = \sqrt{1 - \frac{1}{\alpha^2}} = \frac{\sqrt{\alpha^2 - 1}}{\alpha}. \tag{5}$$

The range is therefore given by Equation (6):

$$R = \frac{v^2 \sin 2\theta}{g} = \frac{2v^2 \sin\theta\cos\theta}{g} = \frac{2u^2}{g}\sqrt{\alpha^2 - 1}. \tag{6}$$

Unsurprisingly, this means that the faster the ball is kicked, the farther it will travel. (Physics also dictates what a kicker can do to strike the ball more effectively, so that its launch speed is higher.[3] And it shows what air drag can do, and how best to kick when faced with a stiff breeze.[4] In Ohio

---

[2] A good introduction to pursuit curves, from a physics perspective, is Carl E. Mungan, "A classic chase problem solved from a physics perspective", *European Journal of Physics*, 26 (2005), 985–990. See also Trevor Davis Lipscombe, *The Physics of Rugby*, pages 66–70. (Nottingham: Nottingham University Press, 2009).

[3] See Timothy Gay, *The Physics of Football*, Chapter 5, "Kicking the Football", pages 129–166. (New York: Harper Collins, 2005).

[4] Trevor Davis Lipscombe *The Physics of Rugby*, Chapter Four, "Kicking, the Habit", pages 95–130. (Nottingham: Nottingham University Press, 2009).

old-fashioned kicking, where the ball is struck with the toe rather than, soccer style, with the instep, is still common.[5])

The hang time, T, is given by Equation (7):

$$T = \frac{2v\sin\theta}{g} = \frac{2u}{g}\sqrt{\alpha^2 - 1}. \tag{7}$$

This means that, no matter what the launch speed, there is always a perfect kick off, one where the ball lands at exactly the time the kickoff coverage arrives.

There is a natural objection, namely, the ball is in the air and often is caught by the receiving team, so there is a height difference between launch and catch. However, at the kicking camps that young college prospects attend, kickoffs and punts are charted from where the ball is kicked to where it lands, so the assumption of a horizontal surface is justified in that case.

The above equations, then, are an approximation, and one could instead use the equations for the range of the ball launched from $y = 0$ and caught at $y = H$.[6] But, as the range for most kickoffs is some 60 meters and the ball is caught at chest height, about 1.5 meters, the approximation should work fairly well.

For punting the situation is significantly more complicated. The height differential is less, as punts are typically kicked at about knee height, unlike a kickoff, which is from the ground or from a small tee. However, the coverage starts sprinting the moment the ball is snapped at time $t = 0$, and the punter kicks the ball some τ seconds later at a distance L behind the line of scrimmage. This means the ideal punt is one given in Equation (8):

$$R = \frac{v^2\sin 2\theta}{g} = u\left(T + \tau\right) + L. \tag{8}$$

---

[5] Ben Keslin, "Old Fashioned Place-Kickers Retain a Toehold in Ohio High Schools," Wall Street Journal https://www.wsj.com/articles/old-fashioned-placekickers-retaina-toehold-in-ohio-high-schools-1379989900 (retrieved June 24, 2020)

[6] See, for example, https://www.usna.edu/Users/physics/mungan/_files/documents/Scholarship/Projectile.pdf

By means of Equations (1) and (2), we can recast this as Equation (9):

$$\frac{v^2 \sin 2\theta}{g} = u\left(\frac{2v\sin\theta}{g} + \tau\right) + L. \tag{9}$$

Consider only those punts for which the range, $R \gg L$, and which are kicked quickly, so that $\tau \ll T$. That is to say, our simpler equation holds for elite punters who kick the ball a great distance, with a large hang time, soon after the snap of the ball.

The Kicking Camp Equation

The criterion expressed in Equation (3) for the ideal punt is unlikely to be achieved in real life. No matter how much a kicker practices, so that the speed with which they kick the ball is very nearly always the same, and the launch angle is close to being constant, there will always be some variation. How, then, can we judge a set of "almost perfect" punts or kickoffs? Or, perhaps more important, how can we determine the hot prospects among high school football kickers, ranking them to see who merits a Division I college scholarship.

One approach of scientific interest is that taken by various kicking camps, such as those arranged by Kohl's and Kicking World. In assessing punts and kickoffs, they award points, P, based on what we call the Kicking Camp Equation (KCE), Equation (10):

$$P = R + uT. \tag{10}$$

Kickers scoring high points at a Kicking World National Showcase, as given by the KCE, garner attention from special-teams coaches at the major football colleges (FBS teams, like Clemson, Alabama, and Notre Dame).

Intriguingly, the KCE, gives a different criterion for kick-off angle than the "perfect" formula of Equation (3).

Written out in full, using Equations (1) and (2), the KCE awards points according to Equation (11):

$$P = \frac{v^2 \sin 2\theta}{g} + \frac{2uv\sin\theta}{g}. \tag{11}$$

Given a launch speed v, we seek to kick off at an angle that will maximize points. That is to say, we seek the angle that maximizes the points, a condition given by Equation (12):

$$\frac{dP}{d\theta}=\frac{2v^2\cos 2\theta}{g}+u\frac{2v}{g}\cos\theta=0. \tag{12}$$

The angle that maximizes the points as given by the KCE is given by Equation (13):

$$\alpha\cos 2\theta+\cos\theta=0, \tag{13}$$

which can be rewritten as Equation (14)

$$2\alpha\cos^2\theta+\cos\theta-\alpha=0. \tag{14}$$

This is the quadratic equation, whose solution is given by Equation (15):

$$\cos\theta=\frac{\sqrt{1+8\alpha^2}-1}{4\alpha}. \tag{15}$$

This differs significantly from the "perfect punt" condition. Namely, given that punts and kickoffs can go 60 meters, suggesting a launch speed of about 25 m/s, and that athletes can sprint at 10 m/s, we have $\alpha\sim 2$. In other words, we can expect that, to a good approximation, the ideal kicking world punt is given by Equation (16):

$$\cos\theta=\frac{1}{\sqrt{2}}-\frac{1}{4\alpha}+\frac{1}{32\sqrt{2}\alpha^3}+\dots. \tag{16}$$

For high launch velocities, this corresponds to a launch angle of 45°.

Hence, the KCE rewards those who kick for maximum range or, to be more exact, who hit the ball at slightly less than 45°.

Those who kick at 45 degrees receive points given by Equation (17):

$$P=\frac{u^2}{g}\left(\alpha^2+\sqrt{2}\alpha\right), \tag{17}$$

whereas those who kick perfectly obtain points given by Equation (18):

$$P=4\frac{u^2}{g}\sqrt{\alpha^2-1}. \tag{18}$$

The KCE points system, then, rewards "Bigfoot" – the person with the "Big Foot" who hits the ball hard at 45 degrees, rather than the kicker whose ball is perfectly synchronized with the coverage. The two points totals are equal for $\alpha = \sqrt{2} = 1.414$ ... But as most kickers have a higher launch speed (over 20 m/s, and thus with $\alpha > 2$) the synchronous kicker is at a disadvantage.

An Improved Kicking Equation

Though the KCE rewards Bigfoot, this is not optimal[7]. If the ball outdistances the coverage, the receiving team can gain many yards before the coverage arrives and, as the receiver is at top speed, he can be difficult to tackle. Consequently, we modify the KCE to penalize those who either over- or under-kick the coverage. That is to say, a ball hit too far should have been angled more steeply, giving less distance but more hang time. A ball hit more steeply, so that the coverage in essence have to wait for it, should have been launched at a shallower angle. Consider the improved kicking equation (IKE), which is a modification of the KCE, and is defined by Equation (19):

$$P = R + uT - \left[R - uT\right]. \tag{19}$$

The farther the kick is from the ideal, the more the kicker is punished. We can express this differently. Namely, if $R > uT$, this reduces to $2R$, but if $R < uT$, it becomes $2uT$. In other words the points awarded obey Equation (20):

$$P = 2\min\left(R, uT\right). \tag{20}$$

There are two distances in play. First is the range of the ball. The second is the distance run by the kicking team coverage. The KCE simply sums these. The IKE doubles whichever of the two is the smallest. This means that if you hit for distance and lose hang time, you score twice the distance your coverage can run during that hang time. If you have a long hang time, you score only twice the distance of the kick.

---

[7] An objection might be that, with a sufficiently hefty boot, a young player can be trained to aim for more hang time. Or, rather, that it might be easier to coach a player who can kick the ball hard to aim for more hang time, than to get a player who punts perfectly to hick for more yards.

A punt at 45° degrees, currently the angle most rewarded by the KCE, generates the following number of points using the IKE, as per Equation (21):

$$P = 2\min\left(\frac{v^2 \sin 2\theta}{g}, \frac{2uv\sin\theta}{g}\right) = 2\min\left(\frac{\alpha^2 u^2}{g}, \frac{\sqrt{2}\alpha u^2}{g}\right), \qquad (21)$$

which reduces to Equation (22):

$$P = 2\sqrt{2}\frac{\alpha u^2}{g}. \qquad (22)$$

For the perfect punt $R = uT$ which would consequently generate the points score according to Equation (23):

$$P = \frac{4u^2}{g}\sqrt{\alpha^2 - 1}. \qquad (23)$$

Again, these two punts are equal for $\alpha = \sqrt{2} = 1.414$ ..., but for alpha greater than this value, the "perfect punt" scores more points.

Discussion

The KCE and the IKE provide different measures of how good a kick is. The KCE rewards those who can blast the ball hard at 45 degrees, whereas the IKE produces a somewhat subtler effect – the punter who can kick 30, 40, or 50 yards and allow the coverage 3, 4, or 5 seconds to get there. This strategy optimizes the net yardage for the punt, as it means in almost all circumstances the receiver – with the coverage breathing down his neck – will opt for a fair catch, with no return.

The question, though, is whether this makes a difference. To do so, we used the data for punts and kickoffs recorded at Kicking World's National Showcase on December 7, 2019.[8] For these, Kicking World uses two separate formulas. For punts, the value of u is set at 11 yds/second, which is a reasonable speed for an elite athlete. For kickoffs, though, a value of 17 yds/second is used. This may seem puzzling, as it is an "equipartition"

---

[8] https://www.kickingworld.com/camp-result/national-showcase-kickoff-charting-december-7–2019/ (retrieved June 24, 2020)

principle of sorts. Namely, by multiplying the hang time by 17, you generate about the same number of yards as the range of the kick. But there is a good football-related reason behind this. Namely, in college, the ball is kicked from the kicking team's 35-yard line. Hence, any kick that goes more than 65 yards lands in the opponents end zone, permitting them to start with the ball at their own 25 yard line, equivalent to a 40 yard kick with no return. The optimal kick off, then, might be one that goes 55 yards, with the largest hang time possible.

The results are intriguing. For punting, the order remains somewhat the same. That is to say, if one uses the KCE those ranked (1,2,3,...10) are ranked 1,2,3,4,5,7,6,9,10,8, which represents a mild shuffling of the top 10 out of the 46 punters whose kicks were charted. The bottom six were ranked 41,42,...46 by the KCE but are ranked (46,42,38, 43,45,44). So, at the top and bottom of the pack, there is only a slight rearrangement of the order.

Kickoffs, though, lead to a substantial reordering. The kickers ranked 1 to 10 by the KCE now become, with the IKE, ranked (1,3,14,25,7,20,4, 25,17). Of the 56 entrants, the bottom 7 (51–56) as ranked by the KCE now become (46,48,47,50,55,56). This suggests that the poorer kickers aren't affected much by whether one uses the KCE or the IKE, but the top ranked kickers are. This is, perhaps, not surprising. By using the multiplier of 17 yds/sec, the KCE rewards hang time significantly more than the IKE. However, changing the multiplier to 11 yds/second in the KCE does not change their ranking of kickers significantly.

The major difference in the rankings, then, is mostly due to the punitive effects of the IKE. Namely, suppose each contestant has two kicks. Kicker A hits two perfect kickoffs, one long, one short. Kicker B hits one long, but with no hang time, while the second one is short, but with plenty of hang time. Kicker B would, as per the KCE, be given the same number of points as Kicker A, as the two sets of kicks are indistinguishable. However, Kicker A would far outscore Kicker B by means of the IKE. In fact, Kicker A might outscore Kicker B with two medium-range perfect punts. Hence, the IKE rewards consistently good kicking. And consistently good kicking is probably what most coaches seek.

Conclusion:

In American football, the kicker's conundrum is that increasing the range decreases the hang time, but both of these are highly prized commodities. By requiring the ball to land at the same moment the kicking team arrives at the same place, we can determine the optimal launch angle for an ideal kick. Various kicking camps assess a kicker's ability according to an empirical formula. This we show rewards those who can kick the ball hard and therefore can be far from the perfect punt. We develop a similar formula, one that simultaneously rewards long ranges, long hang time, but punishes excesses of either. The new equation might be worthy of consideration as a means to find talented high-school kickers seeking a college football career.

Acknowledgment: I thank Peter Lipscombe, whose ability with kickoffs, punts, and field goals initially suggested this problem.

Bio

Trevor Lipscombe trained as a theoretical physicist and played rugby, a sport that -- like football -- features kicking and bloodshed. He is the author of the *Physics of Rugby* and has been interview by the *Irish Times*, among others, for is work on sports-related physics. Trevor works for the Catholic University of America, whose football team won the Orange Bowl and tied for the Sun Bowl -- in 1936 and 1940 respectively.

Science Bite – submitted by Paul Arveson

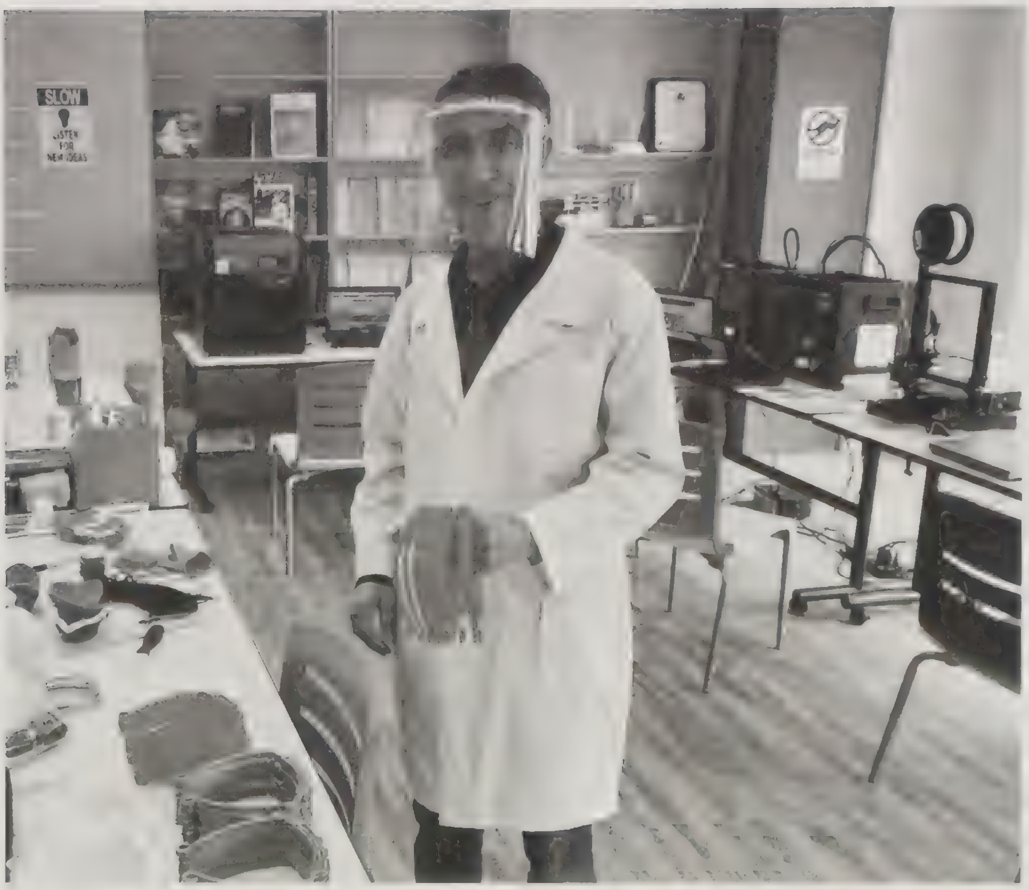
Finally, a Practical Use for 3D Printers!

By the end of March 2020 fear of the pandemic had reached a high level based on stock market data. Grocery stores were cleared of disinfectants and paper supplies. Recognizing the vast demand for PPE one of our members decided to join a small group of local "makers" to fabricate face shields, masks, and the like using 3D printing technology.

He bought a 3D printer for $210 in early April and had it delivered to the local "maker space" (WAS has access to such a space at a retail store front). Working with the manager of the maker space, Abdel Elhamdani, he gathered several 3D printers and proceeded to fabricate a variety of objects, including face masks, face shields, and little straps that support surgical masks behind the head. Working together they produced hundreds of copies of various designs of PPE. (The NIH has set up a 3D Print Exchange website to collect codes that can be used to print these designs). They distributed these to nearby grocers and carry-out shops, as well as to local distribution points that the local county had set up.

When the supply of PPE for health care workers increased, amateur made products were no longer accepted by the health care industry. 3D printing is considered a hobby, not a professional operation. It is difficult to get the printer settings right, and there are many printing failures. However, one remaining product is still in high demand. Nurses need the surgical mask straps, which take stress off their ears from wearing masks all day. So they printed packs of these little devices and delivered a pack of a hundred of these to a nearby hospital. They were gratefully accepted.

They donated the printer to the maker space to be used by the creative young students in the Rockville Science Center in Maryland.



Abdel Elhamdani in the maker space

Science Bite – submitted by Ron Hietala

GPS, its current state and current champion (?!)

Who does not marvel at the extent of science and technology in the Washington, DC area? The innovations that have been accomplished within 50 miles of the Washington Monument would make heads spin, if people thought about it much.

A favorite example is the Global Positioning System (GPS), developed by a team at the Naval Research Laboratory led by Roger Easton. It became functional in 1993. Its original, defining purpose was to enable military pilots to know their locations without sending out any signals that might allow anybody else to know their locations. That concept has been substantially broadened now. Now it is used by drivers to avoid having to know where they are going, boy scouts to know if they are on the right trail, runners to know how far they ran, ship captains to avoid being lost at sea, and other uses too numerous to account.

How much did it cost? If you have to ask, you don't want to know. $12 billion to get it operational. Much more to refine its accuracy. Still more to keep it going.

But here is the funny part of this story. Who do you think is the current champion of global positioning technology? It depends on whom you ask and which of the many purposes of the system are yours to fulfill.

If you are a farmer in the United States, the answer is obvious; it is the John Deere Company.

John Deere sells tractors from 20 horsepower to 620 horsepower, recreational vehicles, and pedal tractors for kids as young as four. Much of the road equipment you see as you drive using your GPS is John Deere. Much of the newest equipment used on farms is made by John Deere.

They also sell a global positioning system that has been refined to a remarkable degree. When the farmer takes the tractor to the field, the computer on the tractor knows the location of the tractor within two centimeters. Not kilometers, not meters – centimeters!

The farmer does not even steer the tractor much. The GPS does that, in combination with the computer. The farmer may drive along the edge of a field and give the steering wheel a nudge when it's about time to turn into the field and start working, but the tractor does not turn immediately. The GPS-computer waits until the machine is an exact multiple of the width of the implement from the edge of the field. There's no need to waste time and fuel by misjudging the distance from the edge of the field, not when you know the location of the tractor within centimeters. If the John Deere-enabled GPS-computer has run this machine on this field before, it also follows in the same tracks it made before, even if they were made in earlier years. This avoids packing additional ground with these machines, which weigh up to 25 tons. Plants grow better in loose soil. Before GPS, farmers typically overlapped, about 10 inches, their routes across the field, to ensure they got the seed, fertilizer and weed chemicals everywhere they were needed. So now they save some expense on those.

How did John Deere achieve this remarkable accuracy? Most of the errors made by the global positioning system are related to locality. Errors result from weather conditions, variations of the location of satellites due to various gravitational forces as the satellites orbit, the slowing of the signal due to atmosphere, and the angles at which the signals go through the gas layers around the earth. Because these errors are relatively consistent within small distances, they can be reduced if the magnitudes of the errors locally are known. John Deere maintains stationary GPS stations throughout its market and broadcasts errors so the farmers' GPS units can correct for the errors. Farmers, and anyone else who wants to spend several thousand dollars, can also buy and maintain their own stationary systems to refine their location estimates.

All that doesn't change the history. The fact remains that all the heavy lifting was done, and the big money spent, by the Naval Research Lab. The U. S. Navy still maintains the system.

What about the future? The mind boggles. Maybe parents will wire their children with electronic devices that will send the kids' precise locations to the parents. Maybe automobiles will routinely carry their own locations and the locations of all nearby vehicles in their computers, so they will be able to roll along the freeways centimeters apart with no fear of collisions. Maybe airplanes will find their own ways down to the runways and traffic control towers will be converted into restaurants. There is more to come, we may be sure; this thing is just getting rolling.

Delegates to the Washington Academy of Sciences Representing Affiliated Scientific Societies

Acoustical Society of America	Paul Arveson
American/International Association of Dental Research	J. Terrell Hoffeld
American Assoc. of Physics Teachers, Chesapeake Section	Frank R. Haig, S. J.
American Astronomical Society	Sethanne Howard
American Fisheries Society	Lee Benaka
American Institute of Aeronautics and Astronautics	David W. Brandt
American Institute of Mining, Metallurgy & Exploration	E. Lee Bray
American Meteorological Society	Vacant
American Nuclear Society	Charles Martin
American Phytopathological Society	Vacant
American Society for Cybernetics	Stuart Umpleby
American Society for Microbiology	Vacant
American Society of Civil Engineers	Vacant
American Society of Mechanical Engineers	Daniel J. Vavrick
American Society of Plant Physiology	Mark Holland
Anthropological Society of Washington	Vacant
ASM International	Toni Marechaux
Association for Women in Science	Jodi Wesemann
Association for Computing Machinery	Vacant
Association for Science, Technology, and Innovation	F. Douglas Witherspoon
Association of Information Technology Professionals	Vacant
Biological Society of Washington	Vacant
Botanical Society of Washington	Chris Puttock
Capital Area Food Protection Association	Keith Lempel
Chemical Society of Washington	Vacant
District of Columbia Institute of Chemists	Vacant
Eastern Sociological Society	Ronald W. Mandersheid
Electrochemical Society	Vacant
Entomological Society of Washington	Vacant
Geological Society of Washington	Jurate Landwehr
Historical Society of Washington DC	Vacant
Human Factors and Ergonomics Society	Gerald Krueger

(continued on next page)

Delegates to the Washington Academy of Sciences Representing Affiliated Scientific Societies

(continued from previous page)

Institute of Electrical and Electronics Engineers, Washington Section	Richard Hill
Institute of Food Technologies, Washington DC Section	Taylor Wallace
Institute of Industrial Engineers, National Capital Chapter	Neal F. Schmeidler
International Association for Dental Research, American Section	Christopher Fox
International Society for the Systems Sciences	Vacant
International Society of Automation, Baltimore Washington Section	Richard Sommerfield
Instrument Society of America	Hank Hegner
Marine Technology Society	Jake Sobin
Maryland Native Plant Society	Vacant
Mathematical Association of America, Maryland-District of Columbia-Virginia Section	John Hamman
Medical Society of the District of Columbia	Julian Craig
National Capital Area Skeptics	Vacant
National Capital Astronomers	Jay H. Miller
National Geographic Society	Vacant
Optical Society of America, National Capital Section	Jim Heaney
Pest Science Society of America	Vacant
Philosophical Society of Washington	Larry S. Millstein
Society for Experimental Biology and Medicine	Vacant
Society of American Foresters, National Capital Society	Marilyn Buford
Society of American Military Engineers, Washington DC Post	Vacant
Society of Manufacturing Engineers, Washington DC Chapter	Vacant
Society of Mining, Metallurgy, and Exploration, Inc., Washington DC Section	E. Lee Bray
Soil and Water Conservation Society, National Capital Chapter	Erika Larsen
Technology Transfer Society, Washington Area Chapter	Richard Leshuk
Virginia Native Plant Society, Potowmack Chapter	Alan Ford
Washington DC Chapter of the Institute for Operations Research and the Management Sciences (WINFORMS)	Meagan Pitluck-Schmitt
Washington Evolutionary Systems Society	Vacant
Washington History of Science Club	Albert G. Gluckman
Washington Paint Technology Group	Vacant
Washington Society of Engineers	Alvin Reiner
Washington Society for the History of Medicine	Alain Touwaide
Washington Statistical Society	Michael P. Cohen
World Future Society, National Capital Region Chapter	Jim Honig

Washington Academy of Sciences
Room GL117
1200 New York Ave. NW
Washington, DC 20005
Return Postage Guaranteed

NONPROFIT ORG
US POSTAGE PAID
MERRIFIELD VA 22081
PERMIT# 888

4*8**********122*****************AUTO**MIXED ADC 207
HARVARD LAW S LIB ERSMCZ
LANGDELL HALL 152
1545 MASSACHUSETTS AVE
CAMBRIDGE, MA 02138-2903