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Supplementary Information for

Better data for sustainable development: Socio-ecologically informed use of remote sensing data to predict rural household poverty

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Other supplementary materials for this manuscript include the following:

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Supplementary Information Text

S1: Detailed description of the multi-level approach

Level 1: Homestead. Homestead areas are used by a household for a variety of purposes, including livestock grazing, woodlots for fruit and timber, agriculture, and drying and processing crops. RS features extracted from homesteads included the amount of woodland, shrub/hedges and the amount of grass - each of which could provide opportunities for income generation or food production. The amount and size of buildings within the homestead was estimated from RS data as larger buildings are potentially related with higher levels of wealth (Table S1 provides more details on the variables extracted from RS data and justifications for the livelihood characteristics for which they may be proxies). In Sauri, we assumed that only households within a homestead boundary had access to these level 1 resources and thus RS features within this area were only related to these households. We manually digitised 1150 homestead polygons across the study site, 231 of which coincided with GPS referenced household survey data from the MVP baseline survey.

Level 2: Agricultural land surrounding homestead. Agriculture is a large contributor to household income in rural areas of developing countries (Nguyen et al. 2015). In Kenya, agriculture accounts for 53% of Gross Domestic Product (GDP) (26% directly, 27% indirectly), and 70% of rural employment (Mutuo et al. 2007) In Sauri, 80% of household heads reported their occupation as farmer or farm labourer in the baseline survey (Mutuo et al. 2007). In small-holder systems such as Sauri, agricultural decisions are made at the individual field level and reflect household characteristics and experience as well as climatic conditions during the growing season. This one-to-one relationship between agricultural fields and the operating household could have a strong relationship with household wealth. Assigning every agricultural field to the operating household would require a detailed field mapping exercise (Walsh et al. 2003), which is time consuming and costly to perform. Based on our knowledge of the spatial proximity of homesteads and their agricultural fields in this area, we linked agricultural (crop land and non-vegetated) land to the nearest household using a pixel-based object-resizing algorithm in eCognition developer 9.2 (Trimble Geospatial http://www.ecognition.com/suite/ecognition-developer). To do this, each classified homestead from level 1 was grown outwards until it hit another homestead boundary. This level, as with Level 1 is considered exclusive use by the household associated with the homestead. Subsequent cleaning removed any areas that were not available for agricultural production, such as schools, markets and communal grazing areas. Homesteads were masked from the land use map prior to estimating the amount of agricultural and non-vegetated/bare land in level 2 polygons to ensure that any agricultural pixels within a homestead could not be linked to additional households.

Level 3: Village Cluster. Non-agricultural environmental resources such as non-timber forest products and grazing land, have been found to contribute up to 27% of household annual incomes in different locations in Sub-Saharan Africa (Monela et al. 2001; Dercon et al. 2009). These often communal resources are extracted from areas around the village including forest areas, hedges around agricultural fields, open grasslands, riparian regions and waterbodies. Level 3 polygons were created using radial buffer zones around each homestead boundary in ESRI ArcMap 10.2. The buffer zones had a radius of 200m, the same as that used in our single buffer approach. The proportions of woodland, grassland, road, homestead and water cover within the buffer zones were calculated to estimate proxies for local resources (Table S1). The proportion of roads and paths within the buffer zones were calculated as a proxy for connectivity (Table S1), where the higher the proportion, the more connected a household may be.

Pixels that had been associated with a household in Level 1 and Level 2 were masked prior to Level 3 extraction. This ensured that woodlots within a homestead would not be associated with another household, while shrub and woodland cover along roadsides, around agricultural field boundaries and denser woodland areas could be associated with numerous households. This reflects the nature of common pool resources more accurately as often they are collected from small spaces across the landscape and members of multiple households may access the same spaces for these resources.

Level 4: Regional area. At the regional level, rural households benefit from access to markets and road infrastructure (Stifel and Minten 2017), although access to transportation is often also required as well as road infrastructure for households to access markets (Bryceson et al 2008). Level 4 considered proximity of households to road infrastructure and also distance to market centre. We estimated Euclidean distance from each homestead to the main all-weather road, identified in the LULC maps, that runs through the region and connects to nearby Yala Town. The same MODIS NDVI time series information used in the single-buffer zone approach was also used here.

S2: Land use class definitions

The crop calendars for Sauri indicate the September acquisition date of the image is between the harvest of the long rain maize crop and planting of the short rain maize crop. Therefore, it may be that the bare ground indicates areas of agriculture that have been harvested at the end of the summer planting season (long rains season). However, with only a single snap shot image available for classifying land use we are not able to add this bare ground to the agricultural land class. This is because field experience has revealed that some agricultural land has failed to rehabilitate due to overuse. So bare ground has been kept as a separate class. Grassland here is defined as any area with extensive grass coverage that is clearly not used for agricultural purposes, it could be grazing but also open communal ground around Churches and Schools. Woodland is defined here as any area with trees which can include woodlots, individual trees and large wooded boundaries around fields. Shrub is defined here as hedges around agricultural field boundaries.

S3: Time Series analysis of MODIS method and calculation of Length of Growing Period.

A grid of 500m cells was created over the study region, and the NDVI value for each 16-day composite was extracted for each cell. Since MODIS pixels of 500m were used each household was linked to the pixel in which it was contained; if a homestead was on the boundary of two or more pixels it was given the average value. A Savitzky-Golay filter with a window size of six was used to smooth the data in TIMESAT software (Jonsson and

Eklundh 2004) to estimate the length of growing period (LGP) per year (Figure S1). The LGP was defined as the sum of the length of both growing periods in each year. Season start and end points were identified as the point where NDVI increased/decreased by 10% of the distance between the minimum and maximum and was computed in the TIMESAT software (Jonsson and Eklundh 2004).

S4: Measuring Household Wealth from survey data and Constructing a Wealth Index

Sauri was part of the Millennium Villages Project (MVP) (Mutuo et al. 2007) and is located in Yala County (formerly part of Siaya District). The area is in the Kenyan highlands, at 1400-m elevation. Households typically live in homesteads, small areas with several structures, gardens or woodlots and a surrounding hedge. Agricultural fields are interspersed between homesteads. Agriculture is the primary livelihood, with maize the main crop and bananas, beans, cassava, kale and sorghum also grown. Rainfall is bi-modal allowing two cropping seasons; the long rains (March – June) during which time the majority of maize crops are grown and the short rains (September to December), which are highly variable and lead to crop failures around 50% of the time (Mutuo et al. 2006). This area is typical of many small-holder farming landscapes in East Africa; it is highly fragmented, densely populated and topographically varied, with a complex mosaic of land cover classes. In 2005, 79% of the Sauri population was living below \$1 per day (1993 PPP) and 89.5% below \$2 per day (Mutuo et al. 2007). The MVP was a development project located in ten high-hunger and poverty villages in Sub-Saharan Africa; it investigated how the MDGs could be achieved through direct investment in rural areas (Sanchez et al. 2007). This particular study was not part of the MVP, but used data from the baseline survey (2005) as it provided a rich geospatial data set on household socioeconomic conditions and LULC. The survey in 2005 was conducted prior to MVP intervention efforts so should have had little or no impact on population-environment relationships

The approach taken for the asset index development created relative wealth in the following way:

$$Relative\ household\ wealth = V_1W_1 + \ldots + V_nW_n,$$

where V are the continuous asset variables and W are the variable weights estimated using a principal components analysis (PCA). The PCA is a data reduction technique that transforms a set of correlated variables into a set of orthogonal (un-correlated) principal components which are linear combinations of the original variables. Seventy-five asset variables were available to construct the index, with particular variables removed if more than 98% or less than 2% of households owned the asset. This resulted in a total of 52 assets being included in the year zero index (23 were removed due to too many or too few households owning the assets). Factor scores from the first principal component were used as weights and multiplied with the original variable. The households were ranked by the index score and grouped into three categories; poorest 40%, middle 40% and wealthiest 20%. The first component, which included x,y,z variables, explained the largest proportion of the total variance (18.1% in total) in the unmeasured variable, which here we assumed to be household wealth, as all household assets were positively correlated with the first principal component (ownership of each of the assets was associated with higher household wealth). The variables with the largest coefficients included: kerosene lamps, wheelbarrows, pressure lamps, cell phones, sofa, iron box (for charcoal), beds, bed nets, spades.

The assets used in the index included furniture (chair, bed, sofa), appliances (torch, lamp, sewing machine, mixer and grinder), cooking stove type (traditional charcoal, improved wood, improved charcoal, gas cooker), electrical items (radio, cell phone, computer, rechargeable batteries, solar panel, black and white television, refrigerator, freezer), transport (bicycle, hand cart, wheelbarrow), farm Equipment (hand hoe, spade, sickle, slasher, rake, power tiller), bednets, and livestock. Two assets were owned by over 98% of the households; table and tin wick lamp. Twenty-one assets were owned by less than 2% of households; electric cooker, electric teapot, electric coil, colour television, ceiling and table fan, computer, CD player, DVD player, refrigerator, freezer, motorcycle or scooter, any motor vehicle, hand pump, animal drawn plough, animal drawn cart, saw, water pump, maize mill, electric heater, donkey.

Categorising the Index. The asset index was converted to three categories, Group 1 was the poorest 40% of households, group 2 the middle 40% of households in terms of asset index score and group 3 was the wealthiest. We experimented with several approaches to categorisation. Using deciles (10) and quintiles (5) resulted in too few sample households in each group and created unstable statistical analysis results. When using Quartiles (4 groups) or we found that many households with the same asset score were placed in different wealth groups. For example, households with the same asset score could end up either at the top of the range for group1 or the bottom of the range for group 2. Splitting the households into three groups reduced this problem somewhat. But using three equally sized bins was still affected by this problem. Using a split of 40, 40, 20 for group 1, group2 and group 3 respectively reduced this problem further.

Time Series analysis of MODIS method and calculation of Length of Growing Period.

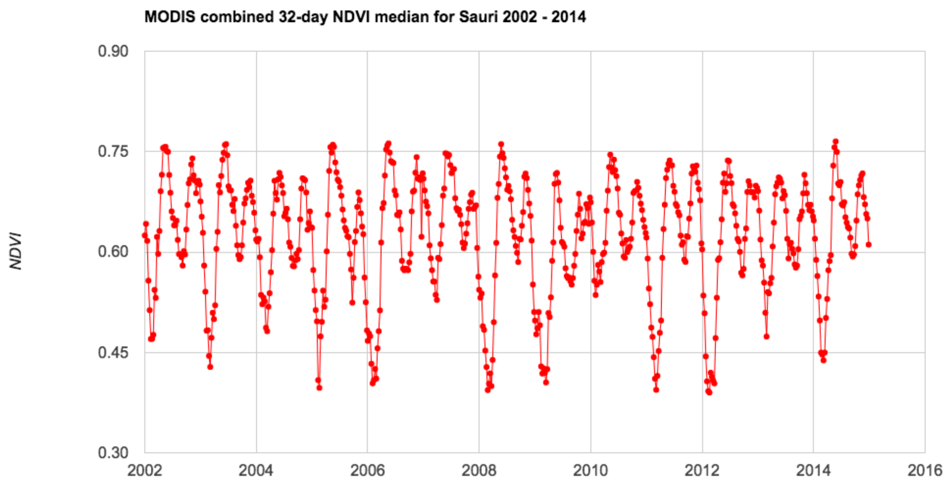

Fig. S1. MODIS NDVI time series averaged over the Sauri Site showing two peaks in NDVI per year which is indicative of a double cropping system.

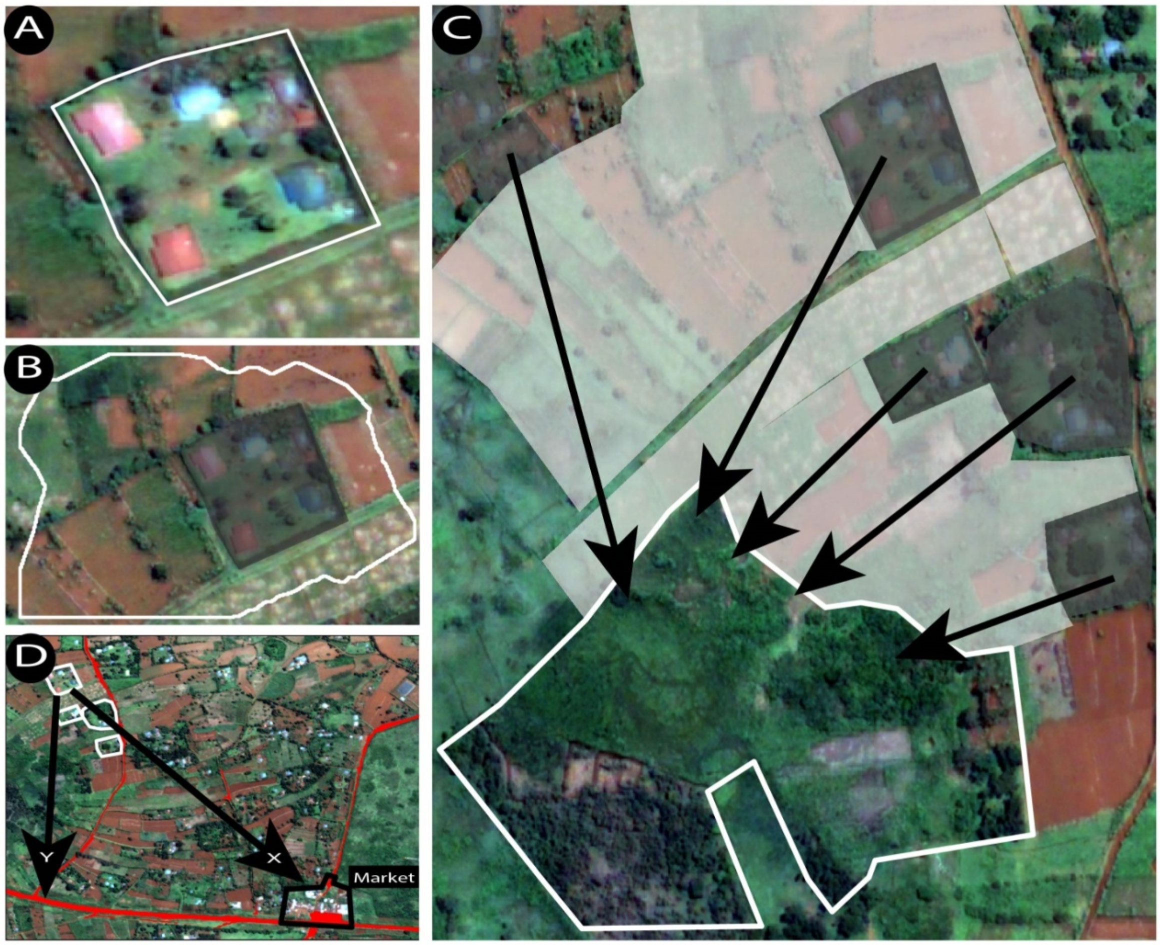

Fig. S2 The multilevel approach in Sauri, Kenya. Inside the homestead area (Level 1) (A), environmental resources are only linked to the single associated household; the agricultural land (Level 2) (B) is linked to the nearest homestead; additional resources (C) may be collected from common-pool woodland and grazing land (Level 3); and the wider regional level (D) (Level 4) considers access to all-weather roads (Y) and the main market centre (X) as well as changes in the MODIS NDVI time series.

Table S1. The fine spatial resolution features extracted from satellite data for predicting household wealth in Sauri. Includes potential relationships that variables may have with rural wealth and type of capital endowments that the features may be proxies for.

Level	Metric	Source	Description	Proxy Capital Endowment	Relationship with Household Wealth	References
Level 1 Homestead	Woody Cover	LULC[1] Map	Proportion of Woody cover inside homestead	• Natural Capital - non-timber forest products, firewood, shade.	• Linear positive: high levels in homestead associated with higher wealth	Mamo et al. (2007); Ndegwa et al. (2016); MEA (2005)
	Grass Cover	LULC[1] Map	Proportion of Grassland inside Homestead	• Physical Capital - grazing land • Natural Capital – pasture for feed	• Either direction. In Kenya households in rangelands are often poorest. grass in homestead could be for protecting and feeding livestock or that the household does not have to use the land productively, perhaps because they have enough land and income from elsewhere.	Okwi et al. (2007); Kristjanson et al. (2010
	Building	LULC[1] Map	Size of the building. Calculated as the size of homestead *	• Financial Capital - investment in domestic buildings.	• Linear positive - large buildings indicate wealthier families	Engstrom et al. (2016); Von Oppen et al. (1997); Windle

			the proportion of homestead covered in building.	• Human Capital – household size, available workers, more potential incomes.	• Linear positive - large buildings indicate more people available to work	and Cramb (1997); Black et al. (2004); Noor et al. (2006); Porter (2002);
	Shrub Cover	LULC[1] Map	Proportion of Shrub cover inside homestead	• Natural Capital - non-timber forest products, firewood, provide habitat for crop pollinators and pest predators, wind protection, prevention of soil erosion, shade. Provision of fruits, agricultural land in fallow.	• Either direction. Could be linked with NTFP and natural resource endowments. But could also be land left in vegetative fallow.	Mamo et al. (2007); Ndegwa et al. (2016);
	Agriculture and Non-vegetated	LULC[1] Map	Proportion of Agriculture or non-vegetated cover inside homestead	• Physical (natural?) capital – agriculture	• Either direction: agriculture in homestead could indicate a lack of agricultural fields elsewhere requiring homestead to be used. Or could indicate higher land use	Zimmerer and Vanek (2016)

					intensities and increased agricultural incomes.	
Level 2 Agricultural Fields	Agriculture	LULC[1] Map	Proportion of the land surrounding homestead covered in Ag, Bare, Shrub	• Physical Capital – availability of agricultural land	• Linear Positive: higher levels of agricultural land indicate higher potential for food security and incomes.	Christiaensen et al. (2006); Ligon and Sadoulet (2008); Christiaensen and Demery (2007)
Level 3 Cluster of households (common pool resource access)	Woodland	LULC[1] Map	Proportion of woodland in buffer zone around the homestead. Homestead and Agriculture masked from the buffer prior to analysis.	• Natural Capital - Common Pool Resources can provide NTFP, timber, firewood, charcoal. provide habitat for crop pollinators and pest predators, • Woodland along field boundaries provide ecosystem services such	• Nonlinear: large amounts of woodland associated with poorer households as indicates isolation. • Nonlinear: small amounts of woodland associated with poorer households as they have fewer ecosystem services and natural capital endowments for income and safety-nets.	Mamo et al. (2007); Ndegwa et al. (2016); MEA (2005); Angelsen et al. (2014); Wunder et al. (2014).

				as erosion control (from wind and rain) • Border protection for land and livestock		
	Grassland	LULC[1] Map	Proportion of grassland in buffer zone around the homestead.	• Natural capital - Providing common pool grazing land	• Either direction. But A mixture of grassland and other natural resources could be beneficial for wealth due to livelihood diversity. Or, commonlands are often degraded lands	Okwi et al. (2007); Kristjanson et al. (2010).
	Water	LULC[1] Map	Proportion of water in buffer zone around the homestead. Homestead and Agriculture masked from the buffer prior.	• Natural Capital - Common pool resource	• Nonlinear: water bodies provide ecosystem provisioning services such as fish and irrigation water. But it needs to be balanced with other resources at this level eg agricultural land, woodland allowing household to pursue diverse livelihood strategy.	Stifel and Minten (2017).
	Homestead Density	Manual Homestead	Number of Homesteads within the buffer zone	• Social capital – information • Human capital	• Either direction • Could be negative as more homesteads in the area could	Engstrom et al. (2016); Von Oppen et al.

		digitisation		• Financial capital –	indicate more competition for resources. • Could be positive as more homesteads could provide potential for more labor, cooperation, and information sharing.	(1997); Windle and Cramb (1997); Black et al. (2004); Noor et al. (2006); Porter (2002);
	Road density	LULC[1] Map	Proportion of roads within the buffer divided by the total area of buffer	• Physical capital – road and market availability	• Linear positive. Paved surfaces in and around the homestead indicates wealth. Higher access to all weather road allows the flow of people and goods to and from markets, education, health care facilities. Also reduces isolation.	Stifel and Minton (2017); Blaikie et al. (2002); Serneels and Lambin (2001); Khandkar et al. (2006).
	CPR[2] connectivity	Patch Analyst in ArcMap 10.2	Connectivity of different woodland patches in the cluster	• Natural capital - More connected patches and large individual patches could mean CPR	• Either direction: well connected woodland patches may provide more ecosystem services.	Adams et al. (2004); Tallis et al. (2008).

[1] Land use land cover map derived from fine spatial resolution satellite data and detailed in Watmough et al. 2017.
[2] Common pool resources

				resources are more resilient to human impacts; allows movement and connection for biodiversity		
Level 4. Regional	Access to All roads; all weather road; markets	LULC[1] & GIS	Distance (m) to any road and distance (m) to all weather road from household	• Social capital - Access to information, • Human capital – access to health services and education • Financial capital – markets??	• Linear and negative: larger distance to roads indicate lower access to important resources and therefore lower wealth. • More roads means household may be able to utilise environmental resources for commercial purposes.	Stifel and Minton (2017); Blaikie et al. (2002); Serneels and Lambin (2001); Khandkar et al. (2006). Okwi et al. (2007).
	Length of Growing Season	MODIS Time Series	Number of days per year that the NDVI[3] is above a given value	• Physical capital – agricultural productivity. Although MODIS resolution means it is measuring	• Linear and positive: Longer growing period linked to lower poverty. Yield is linked with income and poverty and a longer	Okwi et al. (2007); Christiaensen et al. (2006); Ligon and Sadoulet

[3] Normalised Difference Vegetation Index

				vegetation productivity as agricultural land couldn’t be separated.	growing period can be a determinant of yield.	(2008); Christiaensen and Demery (2007); Thongdara et al. (2012); Burke and Lobell (2017).

Table S2: Breakdown of classification tree nodes

Node split	Total number of households	Predicted value – for terminal nodes only	% (total number) of households from G1	% of households from G2	% of households from G3
Building size <140m2	89		61 (55)	33 (29)	6 (5)
Level 2 Nonvegetated <0.125	12	G3	25 (3)	33 (4)	42 (5)
Level 2 Nonvegetated >0.125	77		66 (51)	32 (24)	2 (2)
Level 1 Nonvegetated <0.425	67		63 (42)	37 (25)	0
Y2005 LGP <163 days	41	G1	78 (32)	22 (9)	0
Y2005 LGP >163 days	26	G2	38 (10)	62 (16)	0
Level 1 nonvegetated >0.42	10	G1	90 (9)	0	10 (1)
Building size >140 m2	142		27 (38)	44 (63)	29 (41)
Level 2 Agriculture <0.215	70		37 (26)	41 (29)	22 (15)
NDVI below average <=6years	33	G2	39 (13)	55 (18)	6 (2)
NDVI below average >6years	37		35 (13)	30 (11)	35 (13)
Level 3 homestead <0.165	15	G3	20 (3)	20 (3)	60 (9)
Level 3 Homestead >0.165	22	G1	45 (10)	36 (8)	18 (4)
Level 2 Agriculture >0.215	72	G2	17 (12)	47 (34)	36 (26)

Table S3: T-test results comparing the results from the multi-level and single-level approaches

	t	df	p	95 CI	95 CI
TestAccuracy	19.568	1950.7	0.0000002	0.05	0.06
TreeSize	-6.897	1979.2	0.0000007	-2.912	-1.623
Group1Accuracy	31.969	1984.8	0.0000002	0.098	0.111
Group2Accuracy	2.361	1985.9	0.0183	0.514	0.506
Group3Accuracy	1.922	1118.7	0.0548	-0.0003	0.027

Table S4 Cost break down of High resolution satellite data

Sensor	Band Combination	Spatial resolution	Archive Price	Tasking Price
WorldView 2/3/QuickBird	4 MS bands (B G R NIR) + Pan	Pan = 0.31 – 0.61 m & MS = 1.24 – 2.4	$17.50	$27.50
WorldView 2/3	8 MS bands (C B G Y R RE NIR-1 NIR-2) +Pan	Pan 0.31 – 0.52 MS + 1.24 – 2.08	$19.00	$29.00
SkySat (Planet)	4 MS bands (B G R NIR) + Pan	0.72 m pan & 1 m MS	$9.00	$12.00*

* SkySat has a minimum order of $5,000.
B G R NIR = Blue, Green, Red, Near-Infrared bands
Pan = panchromatic band
MS = multispectral
C B G Y R RE NIR-1 NIR-2 = Coastal, Blue, Green, Yellow, Red, Red-edge, near-infrared 1 and near-infrared 2.

References

1. Adams, W. et al. (2004) Biodiversity conservation and the eradication of poverty, *Science*, 306; 5699; 1146-1149
2. Angelsen, A. et al. (2014) Environmental income and rural livelihoods: A Global-Comparative Analysis, *World Development*, 64(S1); S12-S28
3. Angelsen, A., Wunder, S. (2003) Exploring the Forest-Poverty link: Key concepts, issues and research implications, *Economist*, 40.
4. Babulo, B., Muys, B., Nega, F., Tollens, E., Nyssen, J., Deckers, J., et al. (2009) The economic contribution of forest resource use to rural livelihoods in Tigray, Northern Ethiopia. *Forest Policy and Economics,* 11, 109-117.
5. Black, M., Ebener, S., Najera Aguilar, P., El Morjani, Z., Ray, N. & Vidaurre, M. (2004) Using GIS to measure Physical Accessibility to Health Care. *International Health Users Conference. Washington DC: WHO-PAHO*
6. Blaikie, P., Cameron, J., Seddon, D. (2002) Understanding 20 years of change in West-Central Nepal: Continuity and change in lives and ideas. *World Development*, 30, 1255-1270.
7. Bryceson, D.F., Bradbury, A., Bradbury, T. (2008) Roads to poverty reduction? Dissecting rural roads' impact on mobility in Africa and Asia, *Development Policy Review* 26(4); 459-482
8. Burke, M., Lobell, D.B. (2017) Satellite-based assessment of yield variation and its determinants in smallholder African systems, *PNAS* 114;9 (2189-2194)
9. Christiaensen, L., and Demery, L. (2007) *Down to Earth: Agriculture and Poverty Reduction in Africa*, Washington, DC: The World Bank. DOI: 10.1596/978-0-8213-6854-1
10. Christiaensen, L., Demery, L., and Kuhl, J. (2006) "The Role of Agriculture in Poverty Reduction: An Empirical Perspective" *World Bank Policy Research Working Paper* No. 4013, Washington, DC.
11. de Sherbinin, A., VanWey, L.K., McSweeney, K., Aggarwal, R., Barbieri, A., Henry, S., Hunter, L.M., Twine, W. Walker, R. (2008) *Global Environmental Change,* 18(1); 38-53.

12. Dercon, S., Gilligan, D.O., Hoddinott, J., Woldehana, T. (2009) The impact of agricultural extension and roads on poverty and consumption growth in fifteen Ethiopian Villages, *American Journal of Agricultural Economics,* 91(4); 1007-1021
13. Dewi, S., Belcher, B., Puntodewo, A. (2005) Village economic opportunity, forest dependence and rural livelihoods in East Kalimantan, Indonesia. *World Development* 33(9); 1419-1434.
14. Ellis, F., Bahiigwa, G. (2003) Livelihoods and rural poverty reduction in Uganda, *World Development*, 31(6); 997-1013.
15. Engstrom, R., Hersh, J., Newhouse, D. (2016) Poverty in HD: What does high resolution satellite imagery reveal about economic wealth? *Annual Bank Conference on Development Economics 2016: Data and Development Economics* World Bank, September 2016
16. Henderson, J., Storeygard, A., Weil, D. (2012) Measuring economic growth from outer space, *American Economic Review* 102(2); 994-1028
17. Jönsson, P., Eklundh, L. (2004) TIMESAT – a program for analysing time-series of satellite sensor data *Computers and Geosciences* 39(8); 833-845
18. Khandkar, S.R., Bakht, Z., andKoolwal, G.B. (2006), The Poverty Impact of Rural Roads: Evidence from Bangladesh, *Policy Research Working Paper* No. 3875, Washington, DC, The World Bank.
19. Kristjanson, P., Mango, N., Krishna, A., Radeny, M., & Johnson, N. (2010). Understanding poverty dynamics in Kenya. *Journal of International Development*, *22*, 978-996.
20. Ligon, E., and Sadoulet, E. (2008) Estimating the Effects of Aggregate Agricultural Growth on the Distribution of Expenditures, *Background Paper for the World Development Report 2008*, Washington, DC. The World Bank.
21. Mamo, G., Sjaastad, E., Vedeld, P. (2007) Economic dependence on Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: Synthesis*, Island Press, Washington D.C.
22. Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being Synthesis, island Press, Washington DC.

23. Monela, G.C., Kajembe, G.C., Kaoneka, A.R.S. & Kowero G. (2001) Household livelihood strategies in the Miombo woodlands of Tanzania: emerging trends. *Tanzania Journal of Forestry and Nature Conservation*, 73, 17-33.
24. Mutuo, P. et al. (2007) Baseline Report: Millennium Research Village Sauri, Kenya, *The Earth Institute at Columbia University*, p92 available at: http://mp.convio.net/site/DocServer/Sauri_Baseline_Report_final_3-7-07.pdf (last view 9th May 2018).
25. Ndegwa, G., Anhuf, D., Nehren, U., Ghilardi, A., Ilyama, M. (2016) Charcoal contribution to wealth accumulation at different scales of production among the rural population of Mutumo District in Kenya, *Energy for Sustainable Development* 33; 167-275
26. Nguyen, T., Do, T., Buhler, D., Hartje, R., Grote, U. (2015) Rural livelihoods and environmental resource dependence in Cambodia, *Ecological Economics* 120; 282-295
27. Noor, A.M., Amin, A.A., Gething, P.W., Atkinson, P.M., Hay, S.I., and Snow, R.W. (2006), Modelling Distances Travelled to Government Health Services in Kenya, *Tropical Medicine and International Health*, 11(2), 188–196
28. Okwi, P. O. et al. (2007). Spatial determinants of poverty in rural Kenya. Proceedings of the National Academy of Sciences, 104, 16769–16774
29. Porter, G. (2002), Living in a Walking World: Rural Mobility and Social Equity Issues in Sub- Saharan Africa, *World Development*, 22(2), 285–300.
30. Serneels, S., and Lambin, E.F. (2001) Proximate Causes of Land-Use Change in Narok District, Kenya: A Spatial Statistical Model, *Agriculture, Ecosystems and Environment*, 85, 65–81.
31. Stifel, D., Minten, B. (2008) Isolation and agricultural productivity, *Agricultural Economics*, 39; 1-15.
32. Tallis, H., Kareiva, P., Marvier, M., and Chang, A. (2008), An Ecosystem Services Framework to Support Both Practical Conservation and Economic Development, *Proceedings of the National Academy of Sciences*, 105(28); 9457–9464
33. Thondhlana, G., Muchapondwa, E. (2014) Dependence on environmental resources and implications for household wealth: Evidence from the Kalahari drylands, South Africa, *Ecological Economics*, 108; 59-67.

34. Von Oppen, M., Njehia, B.K., and Ijaimi, A. (1997), The Impact of Market Access on Agricultural Productivity: Lessons from India, Kenya and the Sudan, *Journal of International Development,* 9(1); 117–131.
35. Walsh, S. J. et al. (2003) Integration of Longitudinal Surveys, Remote Sensing Time Series and Spatial Analysis: Approaches for Linking People and Place. In J. Fox, R. Rindfuss, S.J. Walsh and V. Mishra (Eds.), *People and the Environment: Approaches for Linking Household and Community Surveys to Remote Sensing and GIS* (pp. 91-130). Boston: Kluwer Academic Publishers
36. Windle, J., Cramb, R.A. (1997) Remoteness and rural development: economic impacts of rural roads on upland farmers in Sarawak, Malaysia, *Asia Pacific Viewpoint* 38(1); 37-53.
37. Wunder, S., Börner, J., Shively, G., & Wyman, M. (2014). Safety Nets, Gap Filling and Forests: A Global-Comparative Perspective. *World Development*, 64(S1), S29–S42
38. Zimmerer, K., Vanek, S. (2016) Toward the Integrated framework analysis of linkages between agrobiodiversity, livelihood diversification, ecological services and sustainability amid global change, *Land* 5(2); 10-38