Integrated human-earth system modeling–state of the science and future directions: Supplementary Material

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1. Full List of Articles and Categorizations

The complete list of articles, with their citation information, is included as a separate csv file. In this section, we provide additional information on the Integrated Models (Table S1) and other included articles (Table S2).

Table S1: Articles describing Integrated Models, including the Citation, DOI, Classification, and Spatial Categorization

| Citation | DOI | Classification | Spatial |
|----------|-----|----------------|---------|
| 1 Collins et al. (2015) | 10.5194/gmd-8-2203-2015 | Integrated Model | Global |
| 2 Yang et al. (2015) | 10.1007/s11434-016-1175-x | Integrated Model | Global |
| 3 Yang et al. (2015) | 10.1007/s00375-015-5059-6 | Integrated Model | Global |
| 4 Scott et al. (2016) | 10.1007/s10584-016-1602-8 | Integrated Model | Regional-USA |
| 5 Thornton et al. (2017) | 10.1038/NCLIMATE3310 | Integrated Model | Global |
| 6 Leng and Tang (2014) | 10.1175/JHM-D-13-01182.1 | Integrated Model | Regional-China |
| 7 Monier et al. (2015) | 10.1007/s10584-014-1112-5 | Integrated Model | Regional-USA |
| 8 Monier et al. (2013) | 10.5194/gmd-6-2053-2013 | Integrated Model | Global |
| 9 Hejazi et al. (2015) | 10.1073/pnas.1421675112 | Integrated Model | Regional-USA |
| 10 Voisin et al. (2017) | 10.1002/2016WR019767 | Integrated Model | Regional-USA |
| 11 Monier et al. (2013) | 10.1088/1748-9326/8/4/045008 | Integrated Model | Regional-Eurasia |
| 12 Nordhaus (1993) | 10.1016/0928-7655(93)90017-o | Integrated Model | Global |
| 13 Reilly et al. (2007) | 10.1016/j.enpol.2006.01.040 | Integrated Model | Global |
| 14 Monier et al. (2018) | 10.1038/s41467-018-02984-9 | Integrated Model | Global |
| 15 Beckage et al. (2018) | 10.1038/s41553-017-0031-7 | Integrated Model | Global |
| 16 Voldoire et al. (2007) | 10.1007/s00382-007-0225-y | Integrated Model | Global |
| 17 Bahn et al. (2006) | 10.1007/s10584-006-9108-4 | Integrated Model | Global |
| 18 Boumans et al. (2002) | 10.1016/S0921-8300(02)00098-8 | Integrated Model | Global |
| 19 Jarvis et al. (2012) | doi:10.1038/nclimata1586 | Integrated Model | Global |
Table S2: Other included articles, including the Citation, DOI, and Classification

| Citation | DOI | Classification |
|----------|-----|----------------|
| Newell (2012) | 10.1016/j.gloenvcha.2012.03.006 | Commentary |
| Wang et al. (2011) | NA | Commentary |
| Prestele et al. (2017) | 10.5194/esd-8-369-2017 | Commentary |
| van Vuuren et al. (2016) | 10.5194/esd-7-267-2016 | Commentary |
| Johns et al. (2011) | 10.1007/s00382-011-1005-5 | Commentary |
| Palmer and Smith (2014) | 10.1038/512365a | Commentary |
| Moss et al. (2010) | 10.1038/nature08823 | Commentary |
| Hibbard et al. (2010) | 10.1002/joc.2150 | Commentary |
| Lanaak et al. (2013) | 10.1016/j.envsoft.2012.09.006 | Commentary |
| Mauser et al. (2013) | 10.1016/j.cosust.2013.07.001 | Commentary |
| Liverman and Roman (2008) | 10.1002/esp.1715 | Commentary |
| Motesharei et al. (2016) | 10.1093/nsr/nww081 | Commentary |
| Heck et al. (2016) | 10.5194/esd-7-783-2016 | Coupling example |
| Howells et al. (2013) | 10.1038/nclimaiate.1789 | Coupling example |
| Fujimori et al. (2017) | 10.1371/journal.pone.0169733 | Linking tool |
| Meiyappan et al. (2014) | 10.1016/j.ecolmodel.2014.07.027 | Linking tool |
| Bond-Lamberty et al. (2014) | 10.5194/gmd-7-2545-2014 | Linking tool |
| Joshi et al. (2013) | 10.1007/s10584-013-0715-6 | Linking tool |
| Di Vittorio et al. (2014) | 10.5194/bg-11-6435-2014 | Linking tool |
| West et al. (2014) | 10.1088/1748-9326/9/064004 | Linking tool |
| Hurtt et al. (2011) | 10.1007/s10584-011-0153-2 | Linking tool |
| Hurtt et al. (2006) | 10.1111/j.1365-2486.2006.01150.x | Linking tool |
| Fowler et al. (2007) | 10.1002/joc.1558 | Linking tool |
| Wilby and Wigley (1997) | 10.1177/03091339702100403 | Linking tool |
| Mitchell (2003) | 10.1023/A:102603530597 | Linking tool |
| van Vuuren et al. (2010) | 10.1002/wcc.50 | Linking tool |
| Drobinski et al. (2012) | 10.1016/j.envsoft.2012.01.017 | Linking tool |
| Morier et al. (2017) | 10.1088/1748-9326/aa7aee | Review |
| Verburg et al. (2016) | 10.1016/j.gloenvcha.2015.08.007 | Review |
| Keyre (2014) | 10.1002/wene.98 | Review |
| van Vuuren et al. (2012) | 10.1088/1748-9326/72/2024012 | Review |
| Zvoloff et al. (2014) | 10.1007/s00267-012-0009-1 | Review |
| Mueller-Hansen et al. (2017) | 10.5194/esd-8-977-2017 | Review |
| Diaz and Moore (2017) | 10.1038/NCLIMATE3411 | Review |
| Weyant et al. (2017) | doi:10.1093/reep/rew018 | Review |
| Bonan and Doney (2018) | doi:10.1126/science.aam8328 | Review |

2. Detailed Methodology for Figure 5 and Figure S1

Figure 5 in the main text (and Figure S1 in this SM) illustrates the effects of feedbacks from the Integrated Model studies included in this review. Each of these feedbacks effects is shown alongside the results from the Representative Concentration Pathways (RCP; van Vuuren et al., 2011) to provide a sense of the relative size of the effects. We only include studies in this figure that quantify the effect of feedbacks for one of the five identified variables. Several of the studies
(e.g., Boumans et al., 2002; Bahn et al., 2006) develop projections of these variables for alternative scenarios or assumptions using an integrated model, but do not isolate the effect of feedbacks on the results. Jarvis et al. (2012) does isolate the effect of feedbacks. But the authors calculate the feedback parameters required in order to limit temperature to a particular threshold, rather than estimate the effect of feedbacks on temperature rise. These studies are excluded from the figure.

**RCP Data**

CO₂ emissions and CO₂ concentrations for the RCPs are from the official RCP database.¹ Cropland area is from the University of Maryland’s Land Use Harmonization (LUH) website.² Cropland data was upscaled from the gridded maps provided by LUH to global totals. Global mean temperature (GMT) was calculated as the multimodel mean of the GMT in the CMIP5 models. CMIP5 data was accessed from Earth System Grid.³ The data in Figure 5 show the difference in GMT from 1850 in degrees Celsius. Productivity change due to feedbacks is assumed to be zero for the RCPs, as the RCPs were designed excluding climate change effects (see van Vuuren et al., 2011).

**Feedbacks Data**

We extracted the effect of human-Earth system feedbacks on the various variables from the individual articles cited, relying on numbers in text/tables where possible and estimating numbers from figures when necessary (see Table S3). First, we identified the relevant scenario. For studies using the RCPs, this identification was straightforward. For other studies, we chose the closest RCP based on 2100 GMT. We then used the reported differences due to feedbacks to calculate an absolute value for Figure 5 by applying those changes to the RCP data. For example, Voldoire et al. (2007) states that “The annual mean global temperature simulated by the new-coupled system (A2-IM-CM3) is rather similar to the CNRM-CM3 simulation until 2000 (A2-CM3). After 2000, there is a rather abrupt warming of about 0.5 K that is not seen in the A2-CM3 simulation. The difference in mean temperature seems to persist throughout the twenty-first century.” The A2 has similar 2100 GMT to the RCP8.5, so we calculated the temperature in 2000 and 2100 for Voldoire et al. (2007) as the RCP8.5 GMT plus 0.5K. Table S3 includes each of the statements and calculations used. Note that in many cases there were full time series of data in the figures from the original studies, but we did not include these time series in Figure 5.

¹ Database url: http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about
² LUH url: http://luh.umd.edu/data.shtml#LUH1_Data
³ See https://esgf-node.llnl.gov/search/cmip5/
Figure S1. Change in key RCP variables (CO₂ emissions, CO₂ concentration, GMT, land productivity, and cropland area) due to feedbacks at the end of the century (2094 for Thornton et al., 2017; 2100 for all other studies). The y-axis indicates no change from the original RCPs. Dots indicate the change due to feedbacks shown in each study. Colors indicate the RCP used for the reference calculation (red = RCP8.5, pink = RCP6.0, blue = RCP4.5, green = RCP2.6). For studies that were not based on the RCPs, we use the closest RCP in terms of 2100 global mean temperature rise and not the original reference scenario.