

Linking local impacts to changes in climate - a guide to attribution

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Abstract

Assessing past impacts of observed climate change on natural, human and managed systems requires detailed knowledge about the effects of both climatic and other drivers of change, and their respective interaction. Resulting requirements with regard to system understanding and long term observational data can be prohibitive for quantitative detection and attribution methods, especially in the case of human systems and in regions with poor monitoring records. To enable a structured examination of past impacts in such cases, we follow the logic of quantitative attribution assessments, however allowing for qualitative methods and different types of evidence. We demonstrate how multiple lines of evidence can be integrated in support of attribution exercises for human and managed systems. Results show that careful analysis can allow for attribution statements without explicit end-to-end modeling of the whole climate-impact system. However care must be taken not to overstate or generalize the results, and to avoid bias when the analysis is

31 motivated by and limited to observations considered consistent with climate change
32 impacts.

33

34 **Key words:** Observed Impacts of Climate Change, Impact Detection, Attribution, Human
35 and Managed Systems, Multiple drivers

36 This manuscript contains a total of 8.038 words

37

38 **1 Introduction**

39 Human interference with the climate system has been visible at global scales for some
40 time, and is increasingly becoming apparent at regional scales (Stott et al 2010; Bindoff et
41 al 2013). Consequently, the rigorous attribution of changes in local environmental
42 conditions to changes in climate, and specifically the detection of climate change impacts
43 in human systems and sectors interlinked with them, is gaining importance and public
44 attention. Recent assessments of historical responses to climate change have drawn upon
45 large amounts of direct observational evidence, applying formalized procedures for the
46 detection and attribution of observed impacts
47 (Rosenzweig & Neofotis 2013; Cramer et al. 2014).

48

49 While impacts of recent climate change are now documented for all continents and across
50 the oceans, geographical imbalances and gaps in the documentation of impacts for
51 human and managed systems remain. Based on scientific knowledge about the sensitivity
52 of many human and managed systems to weather and climate variability, it is plausible to
53 expect that recent climate change will have had a role in locally observed changes.
54 However, confident detection of local effects in historical data remains challenging due to
55 naturally occurring variability in both climate and potentially impacted systems, and the
56 influence of other important drivers of change, such as land use, pollution, economic
57 development and autonomous or planned adaptation (Nicholls et al 2009; Bouwer 2011;
58 Hockey et al 2011). Often, the specification of a numerical model representing the entire
59 climate-impact system may not be feasible. In those cases, the careful examination of the
60 individual steps of the causal chain linking climate to impacts can still provide insight into
61 the role of recent climate change for the system in question. The goal of this paper is to
62 provide guidance for such an approach to the detection and attribution of impacts of
63 observed changes in climate.

64

65 Detection and attribution refer to the identification of responses to one or several drivers
66 in historical observations, and a range of corresponding methods exists across research
67 disciplines (Stone et al 2013). In the context of climate change research, detection and

68 attribution methodologies have been developed mostly in the field of physical climate
69 science, where a substantial literature presents various model based statistical
70 approaches to the question how effects of anthropogenic forcing can be identified in
71 historical climate data (see Barnett et al 1999; Hegerl et al 2007; Bindoff et al 2013).
72 In contrast, efforts to develop overarching methods for the detection and attribution of
73 observed impacts to climate change are limited (Stone et al 2009; Hegerl et al 2010; Stone
74 et al 2013). Studies explicitly attributing individual observed impacts of climate change to
75 anthropogenic forcing of the climate system are rare, and usually based on a combination
76 of process- or statistical models and climate models (Gillett 2004; Barnett et al 2008;
77 Christidis et al 2010; Marzeion et al 2014). In addition, methods have been developed to
78 evaluate the role of anthropogenic forcing in large-scale patterns of multiple local
79 impacts, mainly in ecology. These include the identification of so-called fingerprints of
80 anthropogenic climate change in large sets of biological data (Parmesan and Yohe 2003;
81 Root et al 2003; Poloczanska et al 2013), joint attribution (Root et al 2005), and joint
82 attribution combined with spatial pattern congruence testing (Rosenzweig et al 2007;
83 2008). Generally, these approaches aim at the identification of a generic impact of
84 anthropogenic climate change which would emerge from analyzing a large number of
85 cases in parallel, given that it is often not possible to confidently attribute changes in
86 individual local records to anthropogenic forcing for technical reasons (Rosenzweig and
87 Neofotis 2013; Parmesan et al 2013).

88

89 The vast majority of impact studies are concerned with the identification of effects of
90 regional changes in one or several climate variables in the context of multiple interacting
91 drivers of change (Cramer et al 2014). Methods for detecting and explaining change are a
92 key part of many disciplines studying natural, human and managed systems, and can be
93 applied in the context of attribution to climate change. For example, reliable process-
94 based models have been developed and applied in climate attribution analysis for some
95 species and crops (Battisti et al 2005; e.g., Brisson et al 2010; Gregory and Marshall 2012).
96 Statistical models are increasingly being used to assess large scale effects of recent climate
97 change (e.g., Lobell et al 2011b; Cheung et al 2013). However, explicit numerical
98 modeling of the climate – impact system is not always feasible (see also section 2).

99 Instead, conclusions about cause and effect are often inferred from a combination of
100 multiple lines of evidence, such as process understanding, local knowledge, field and
101 model experiments, observations from similar systems in other locations, or statistical
102 analysis of observational data (see section 3).

103

104 Below, we will focus on impact detection and attribution in a multi-step analysis, based on
105 a structured examination of multiple lines of evidence. In doing so, we follow the
106 approach proposed by Stone et al. (2013), and applied in Cramer et al. (2014) and
107 elsewhere in the WGII contribution to the fifth assessment report (IPCC 2014a; IPCC
108 2014b). This approach is inspired by the framework laid out by the IPCC good practice
109 guidelines for detection and attribution related to anthropogenic climate change (Hegerl
110 et al 2010), but introduces the important modification that **impact detection** “addresses
111 the question of whether a system is changing beyond a specified baseline that
112 characterizes its behavior in the absence of climate change” (see also IPCC 2014c).

113

114 Detection of change in the climate system is concerned with the identification of a signal
115 or trend beyond the short term variability caused by internal processes. However, the
116 underlying assumption of a stable natural baseline state, with stochastic-like variability
117 superimposed may not be valid or practical in the case of some impact systems,
118 particularly those involving humans. Many impact systems are undergoing constant
119 change due to internal dynamics as well as external drivers which often interact and
120 change over time. The observation of a trend in the overall behavior of such a system, or a
121 lack thereof, may not, on its own, be informative for assessing whether a response to
122 climate change or any other driver has been detected (see also section 2). The main
123 concern of impact detection is to identify the effect of climate change against that of
124 other drivers of change. Therefore, the detection of a climate change impact must involve
125 the explicit testing for confounding factors. In that sense, **impact detection** can't be
126 entirely separated from attribution (see Stone et al 2013).

127

128 In this paper we discuss the major steps involved in a complete evaluation of the causal
129 chain from recent changes in climate to locally observed impacts. Following this

130 introduction, we outline the required steps for a comprehensive impact detection and
131 attribution analysis in section 2. We focus on distinguishing the effects of climate change
132 from those of non-climate drivers, rather than evaluating the anthropogenic contribution
133 to the observed change in climate. In section 3, we apply the resulting procedure in an
134 analysis of several examples from human and managed systems, based on available
135 literature. Those cases illustrate some of the major challenges involved, including the
136 treatment of systems undergoing change from multiple drivers, and the integration of
137 different types of evidence. We further discuss those challenges, and the limits and values
138 of the detection and attribution of climate change impacts in section 4, and provide brief
139 conclusions in section 5.

140 **2 The five steps of an impact detection and attribution analysis**

141 The logic of quantitative detection and attribution analysis - if not the methods - can also
142 be applied to qualitative studies, and those that combine various sources of evidence.
143 That logical flow follows from a classical hypothesis test. Briefly, to test whether climate
144 change has had an effect on a system, a suitable regression or other model reflecting the
145 knowledge of the system is specified. This model includes a possible effect due to climate
146 change as well as other potentially influential factors. The statistical test is then based on
147 comparing the goodness of fit of the model with climate change to that of the model
148 without climate change. In both cases, the model is fitted by optimizing a measure of the
149 goodness of fit. If the correctly specified model that includes the effect of a changing
150 climate provides a significantly superior fit than the model that does not, we conclude
151 that the data are not consistent with the null hypothesis that climate change has not had
152 an effect: in other words, we have detected a climate change impact. If we are also
153 interested in the magnitude of the contributions of the various drivers, the fitted model
154 provides a way of assessing these (e.g., based on the regression parameters).

155
156 The focus on impacts of recent climate change mostly restricts attention to cases in which
157 the design involves a trend in climate (which may, in turn, be consistent with the effect of
158 anthropogenic forcing). The identification of a trend over time in relevant climate
159 variables is therefore part of the analysis. It is important to note that in order to avoid

160 bias, the hypothesis taken as the starting point should not be formulated from the same
161 data used to test it. Rather, it may be drawn from theory, e.g. model predictions, or
162 independent data, such as observations in a similar system in a different location. It can
163 also be helpful to differentiate between known external drivers of a system, which are
164 explicitly accounted for in the specification of the baseline behavior, and confounding
165 factors such as measurement errors, data bias, model uncertainty, and influences from
166 other potential drivers that are not explicitly considered in the study set-up, but need to
167 be controlled for (Hegerl et al 2010).

168

169 Below, we outline the major steps involved in a comprehensive detection and attribution
170 analysis in the context of climate change impacts (see figure 1).

- 171 1) Hypothesis formulation: Identification of a potential climate change impact;
- 172 2) Observation of a climate trend in the relevant spatial and temporal domain;
- 173 3) Identification of the baseline behavior of the climate-sensitive system in the
174 absence of climate change;
- 175 4) Demonstration that the observed change is consistent with the expected response
176 to the climate trend, and inconsistent with all plausible responses to non-climate
177 drivers alone (impact detection);
- 178 5) Assessment of the magnitude of the climate change contribution to overall
179 change, relative to contributions from other drivers (attribution).

180

181 **Figure 1: Schematic of the five steps of detection and attribution of observed climate
182 change impacts. Note that in practice the specification of the baseline behavior and the
183 detection and attribution steps may be performed in parallel, given they all require
184 explicit examination of all drivers of change in the system.**

185

186 **2.1 Hypothesis**

187 A common source of hypothesis is a prediction of an effect of expected anthropogenic
188 climate change based on system understanding. For example, if an impact of future
189 anthropogenic climate change has been predicted in an earlier analysis, one could test

190 whether that effect is now detectable in accumulated observations. Another source might
191 be the detection of impacts in similar systems in other locations, or observations from the
192 recent past, or from paleo records. Naturally, studies will also be motivated by
193 observations of change in the climate-sensitive system; while it is unrealistic to ignore that
194 motivation, efforts need to then be made to minimise the effect of the resulting selection
195 bias or to evaluate its importance (Menzel et al 2006). A central part of this first step is the
196 identification of metrics that characterise the expected response of the system to climate
197 change.

198 **2.2 Climate trend**

199 In order to detect an impact of observed climate change on a system, the climate must
200 actually have changed and also have been observed to have changed for the relevant
201 location and period. This condition distinguishes an impact study from a pure sensitivity
202 analysis. Climate change is defined by the Intergovernmental Panel on Climate Change
203 (IPCC) as “a change in the state of the climate that can be identified (e.g., by using
204 statistical tests) by changes in the mean and/or the variability of its properties, and that
205 persists for an extended period, typically decades or longer” (IPCC 2014c). In that sense,
206 we consider a change in climate any long-term (e.g. 20 years and more) trend in a climate
207 variable that is substantial in relation to short time scale variability, regardless of the
208 cause of that trend.

209

210 A local climate trend is not necessarily caused by anthropogenic climate change. While it
211 is plausible to assume that a local temperature trend that is consistent with the
212 temperature trend in the larger area, which in turn has been attributed to global climate
213 change, may also be caused by anthropogenic forcing, this must not be taken as proven. In
214 general, individual and local climate records show higher variability than aggregated or
215 global measures (Bindoff et al 2013). Local climate is influenced by topography and
216 turbulence, but also by other local factors such as water management or land use change.
217 As a result, local trends may run contrary to or enhance the global warming signal, or may
218 not emerge at all. Changes in atmospheric circulation patterns, or multidecadal natural
219 variability could also generate local trends that differ from global ones. The question of

220 how one might determine whether an observed trend is anthropogenically forced is
221 beyond the scope of this paper, but has been considered elsewhere (Stott et al 2010).
222
223 Systems may be sensitive to aspects of the climate other than the average, such as
224 temperature exceeding 30°C during a certain period in plant development (e.g., Lobell et
225 al 2011a). The chosen metric needs to reflect this aspect of the expected climate change.

226 **2.3 Baseline**

227 For some situations, the identification of a deviation from baseline behavior is relatively
228 straightforward: the metric shows a trend consistent in direction and magnitude with
229 what one would expect under climate change, and that trend is also inconsistent with
230 what could be plausibly expected as the effect of one or a combination of other known
231 drivers in a stationary climate, either because those drivers are of insufficient magnitude
232 or they mutually cancel. However in most human and managed systems, we expect the
233 observed overall response to be consistent with the combined effect of climate change
234 and other drivers, but not with that of climate change alone. The failure to account for all
235 drivers in the baseline may lead to erroneous conclusions about the influence of climate
236 change on a system, as illustrated in Figure 2

237
238 **Figure 2 Stylized examples of the time series of some measure representing a climate**
239 **sensitive system which is responding in time to multiple drivers, one of them climate**
240 **change (the corresponding time series of the climate variable for both cases is shown in**
241 **panel c). The black line depicts the overall behavior of the system, while the dark,**
242 **vertically striped area represents the combined effect of non-climate drivers under**
243 **stationary climatic conditions, and the light area represents the additional effect due to**
244 **recent climate change. In panel a, the baseline condition (dark area) shows a clear**
245 **change midway through the record (e.g. due to a policy measure) but this is**
246 **compensated by the influence of climate change. However the resulting overall measure**
247 **does not show a deviation from its historical pre-climate change trend, thus masking the**
248 **existing climate change effect (potential type I error). In panel b, the observed behavior**
249 **shows a change that is consistent in direction with a predicted climate change impact;**

250 **however, the majority of that change happens due to a change in the baseline arising**
251 **from other factors. This situation could lead to erroneous detection (potential type II**
252 **error) or an overstatement of the climate effect.**

253

254 So, in order to evaluate whether a climate change effect has been observed the baseline
255 behavior of the system *in the absence of climate change* has to be specified (Stone et al
256 2013). For some systems, that behavior may be non-stationary even in the absence of all
257 drivers.

258

259 As a world without climate change cannot be observed directly, the baseline must be
260 constructed using statistical techniques, observations of analogous systems, and/or
261 system understanding expressed in the form of numerical or conceptual models.
262 Specifying a reliable model is often hampered by lack of data, incomplete knowledge on
263 processes and mechanisms involved in systems undergoing change from multiple
264 stressors, limited understanding of causality within complex networks of social systems,
265 and how climate drivers and their perception influence those. In addition, research in
266 qualitative social sciences focuses on descriptive, non-numerical understanding of how
267 systems behave and interact and is often site- or case specific. For a comprehensive
268 assessment of impacts on humans systems, expectations of baseline behaviour may have
269 to be developed and adopted based on qualitative methods.

270 **2.4 Impact Detection**

271 For natural, human and managed systems, impact detection addresses the question
272 whether a system is changing beyond a specified baseline that characterizes behavior in
273 the absence of climate change (IPCC 2014c). In other words, impact detection requires the
274 demonstration that an observed long-term change in a system cannot be fully accounted
275 for by non-climate drivers. So, in order to detect an impact, it is not sufficient for climate
276 change to be a plausible explanation, but it must also be shown that there is no (equally
277 valid) alternative mechanism for the observed change (see also Figure 2).

278

279 In well-observed systems, a common way to investigate the effect of a driver on an
280 outcome in the presence of other drivers is multiple regression analysis. To detect a
281 climate change impact, the null hypothesis that climate change has not affected the
282 outcome has to be tested, controlling for the impact of other drivers and confounding
283 factors, including autonomous and planned adaptation. If the null hypothesis is rejected
284 using a correctly specified model, a climate change impact has been detected. Following
285 this statistical approach, a detection statement is always binary: an impact has (or has
286 not) been detected at a chosen level of significance.

287

288 However, in many systems of interest, quantitative models representing causal
289 relationships will be either impossible to construct or incompatible with the type of data
290 available. In these situations not amenable to statistical testing, a detailed discussion of
291 the role of other drivers and potential confounding factors such as measurement errors or
292 data bias may provide a thorough evaluation of the various hypotheses. Though not
293 directly comparable to the results of a rigorous analysis of long-term data, a clear and
294 comprehensive qualitative analysis represents a valid form of evidence that should not be
295 dismissed.

296 **2.5 Attribution**

297 Attribution needs to examine all drivers of change that influence the system, and evaluate
298 their relative contribution to the detected change. Impact detection implies that climate
299 change has had at least a minor role in the observed outcome. Assessing the magnitude
300 of the contribution of climate change to an impact is a separate, but equally important
301 matter in a detection and attribution exercise.

302

303 An attribution statement needs a qualifier describing the relative importance of climate
304 change to an observed impact. This involves either simply an ordinal statement (e.g.
305 climate is the main influence responsible for a change) or a cardinal statement, which of
306 course requires estimation of the exact relative magnitude of the contribution of climate
307 change in relation to other drivers (see also Stone et al., 2013). The descriptor relates to
308 the size of the response to the climate driver relative to that to other drivers of change in

309 the system, regardless of the direction of that change. While it may be relevant in other
310 ways, the absolute size of the impact is not vital to the attribution statement.
311 A key challenge for all attribution exercises consists of accounting for non-additive effects
312 of multiple drivers interacting on several temporal and spatial scales (see Parmesan et al
313 2013; Oliver and Morecroft 2014). While of particular concern for human and managed
314 systems, such effects have also been shown in analyses of large datasets of biological
315 changes (Crain et al 2008; Darling and Cote 2008).

316

317 **3 Impact attribution assessments – examples from human and managed 318 systems**

319 In this section we provide examples which illustrate the challenges of thorough
320 assessments of climate change impacts. The examples were chosen to cover a range of
321 different conditions in terms of quality and type of evidence, and clarity of climate trends
322 and observations. In line with the focus of this paper, we selected examples from human
323 and managed systems, and from world regions that are currently underrepresented in the
324 literature. The assessments are based on available literature at the time of writing, and
325 provide a summary of the more complex considerations detailed in the underlying
326 literature. As detection is a necessary condition for attribution, the attribution step is
327 omitted in cases where a climate impact has not been detected.

328 **3.1 Fisheries productivity on Lake Victoria**

329 **3.1.1 Hypothesis**

330 The inland fisheries of the Great Lakes are an important food source for the human population of
331 Eastern and Southern Africa, with Lake Victoria having the largest freshwater lake fishery in the
332 world. An expected outcome of anthropogenic climate change is warming of the Great Lakes,
333 with faster warming at the surface increasing stratification (Lehman et al 1998; Verburg and
334 Hecky 2009). Along with direct effects of the warming, the increased stratification is expected to
335 limit nutrient recycling, consequently leading to increased abundance of algae and hypoxic
336 conditions detrimental for the large fish which support the regional fishery industry (Lehman et al

337 1998). Hence, the fishery catch per unit effort would be expected to have decreased on
338 Lake Victoria.

339 *3.1.2 Climate trends*

340 Atmospheric warming has occurred in the Great Lakes region (Verburg and Hecky 2009; Ndebele-
341 Murisa et al 2011), and lake surface waters appear to have warmed, too (Sitoki et al 2010; Loiselle
342 et al 2014). Analyses of sediment cores suggest that the surface waters of other large Great Lakes
343 have warmed to temperatures unprecedented in at least the last 500 years (Tierney et al 2010;
344 Powers et al 2011). A strengthening of the thermocline (and hence increase in stratification) has
345 been observed before 2000, but appears to have weakened since, possibly due to variability in
346 local wind regimes (Stager et al 2009, Sitoki et al 2010).

347 *3.1.3 Baseline*

348 The Great Lakes region has experienced a number of major environmental changes over the past
349 few decades. The Nile Perch, a large predatory fish, and the Nile Tilapia were introduced in 1954-
350 1964, and now comprise the bulk of the catch on Lake Victoria (Hecky et al. 2010). A fundamental
351 and rapid change in the fish community occurred in the early 1980s, and fishing effort has
352 increased in recent decades (Kolding et al 2008). The invasive spread of the water hyacinth had
353 disrupted lake access and transport on Lake Victoria in the 1990s until the more recent
354 introduction of the weevil (Hecky et al. 2010).
355 Much of the land surrounding Lake Victoria has been converted to agriculture, leading to
356 increased runoff of nutrients (Stager et al 2009; Hecky et al 2010). Like warming, this would be
357 expected to contribute to increased eutrophication, increased thermal stratification (by increasing
358 algal abundance), and a shift in species composition and decreased species diversity.

359

360 *3.1.4 Impact Detection*

361 The dramatic rise in both absolute fish catch and catch per unit effort observed on Lake Victoria
362 during the 1980s coincided with the large-scale establishment of the introduced Nile Perch.
363 Altered predation dynamics due to a change in the light regime caused by the increased
364 abundance of algae facilitated the success of the Nile perch (Kolding et al 2008; Hecky et al 2010).
365 Another marked rise in catch of a native species in the 2000s is temporally linked to improved lake
366 access after the establishment of efficient control of the water hyacinth (Hecky et al 2010). That

367 rise is not reflected in other species and the relation to catch per unit effort is not documented;
368 the Nile perch catch has been stable since the 1980s despite increased effort.
369
370 These catch changes are linked to other changes in the ecology of the lake which indicate the
371 possible ultimate causes. Increases in primary productivity and algal abundance were
372 documented in the decades before 2000, though both may have decreased since (Stager et al
373 2009; Hecky et al 2010; Sitoki et al 2010; Loiselle et al 2014). Increases are consistent with
374 warming, increased nutrient supply from agricultural development, and decreased abundance of
375 planktivorous fish species caused by the introduced predators (Hecky et al 2010); the possible
376 recent decrease in algal biomass could be indicative of a decreased catch per unit effort, as
377 decreases in abundance of large predators allows populations of smaller fish species to recover.
378 While the expected effects of species introductions can be distinguished from the expected
379 response to warming, the responses to increased agricultural runoff and increasing fishing effort
380 are harder to differentiate. Thus, while current evidence may suggest a response to warming
381 beyond the responses to other drivers, considerable uncertainties remain.

382

383 *3.1.5 Attribution*

384 While anthropogenic climate change may become the dominant driver of the biology and
385 productivity of the Great Lakes in future decades, current evidence is unable to distinguish
386 whether the influence of warming has already been comparable to or much smaller than that of
387 other drivers of environmental change in the region.

388

389 **3.2 Crop production in Southeast South America**

390 *3.2.1 Hypothesis*

391 In Southeast South America, significant increases in summer crop productivity, and the
392 expansion of agricultural areas have been observed over the last decades. Given that
393 agricultural activity in the region is often constrained by the amount of rainfall, wetter
394 conditions are expected to have contributed to these trends.

395 3.2.2 *Climate trends*

396 Southeast South America refers to the South American area south of 20°S and east of the
397 Andes, excluding Patagonia, and includes the important agricultural production centre of
398 the Argentinean Pampas, South-Eastern Brazil, Paraguay and Uruguay. Past precipitation
399 and temperature trends are well documented over the area (Giorgi 2002; Barros 2010;
400 Magrin et al 2014). The region has warmed by roughly 1°C since the mid 1970s, and the
401 frequency of warm nights has increased. Over the same period, there has been a
402 reduction in the number of overall dry days (Rivera et al 2013) and dry months in the
403 warm season (Vargas et al 2010), and increases in precipitation, leading to a westward
404 shift of the 600 and 800 mm isohyetal lines (Barros 2010; Doyle et al 2011).

405 3.2.3 *Baseline*

406 Across the region, socioeconomic factors such as policy incentives, market conditions,
407 population growth and agronomic developments have positively affected cultivated area
408 and agricultural productivity. The introduction of short-cycle soy varieties, no-till cropping
409 systems, and a general intensification of agriculture following macro-economic
410 development contributed to the expansion of agricultural activities into formally marginal
411 land (Baldi and Paruelo 2008; Asseng et al 2012; Hoyos et al 2013).

412 3.2.4 *Impact Detection*

413 Agricultural activity in the region is predominantly rain fed. The wetter and partly warmer
414 conditions observed since the 1970s are consistent with varying, but substantial increases
415 in yields observed in particular in those areas of Argentina, Uruguay and Southern Brazil
416 where precipitation was the limiting factor in the first half of the century (Magrin et al
417 2005; Magrin et al 2007). In the semi-arid and sub-humid areas at the western and
418 northern fringe of the Argentinean Pampas, increases in precipitation enabled a shift of
419 the “agricultural frontier” of about 100 km to the West into formally semi-arid land
420 (Barros, 2010).

421

422 In order to examine the role of different drivers in the expansion of agricultural land, Zak
423 et al. (2008) and Hoyos et al. (2013) study the conversion of Chaco forest into crop- and

424 rangelands in an area at the Northern fringes of the Argentinean Pampas. They show that
425 conversion rates in the Western part of their study region, which did not experience
426 increases in precipitation, are considerably lower than those in the Eastern part, where
427 they document upward trends in precipitation. As both regions exhibit otherwise very
428 similar conditions, they conclude that climate change is an important enabling factor of
429 the observed agricultural expansion, synergistically with technological changes and
430 socioeconomic drivers. The case is less clear for the La Plata basin, where no such natural
431 comparative area has been identified and studied, and the pattern of land types
432 converted does not allow for a clear distinction of the role of the climate trends (Baldi and
433 Paruelo 2008) as opposed to other factors.

434

435 Magrin et al. (2005) use crop models to study the relative effects of observed changes in
436 temperature and precipitation on yields in the Argentinean Pampas. They examine
437 observed yields of four main crops (sunflower, wheat, maize and soy) in nine
438 representative zones across the region. They conclude that climate change had non-
439 negligible favorable effects beyond that of technological changes. In a similar exercise for
440 six zones that extended to locations in Uruguay and Brazil, Magrin et al. (2007) found
441 substantial positive climate change effects on yields in particular for summer crops. Effects
442 were strongest in the originally drier regions.

443 **3.2.5 Attribution**

444 Recognizing what Zak et al. (2008), call “synergistic consequences of climatic,
445 socioeconomic, and technological factors”, climate change is estimated to be a major
446 driver of the observed increases in summer crop yields and of the expansion of
447 agricultural land into the formally semi-arid regions of South Eastern South America,
448 while the magnitude of its role for other areas and crops is less clear.

449 **3.3 Agroforestry systems in the Sahel**

450 **3.3.1 Hypothesis**

451 Drought and heat induced tree mortality is increasingly reported from many locations
452 worldwide (Allen et al 2010). The pronounced drought over the Western Sahel for much

453 of the second half of the 20th century would be expected to result in negative impacts on
454 agroforestry systems.

455 *3.3.2 Climate trends*

456 Rainfall decreased markedly over the western Sahel in the few decades after 1950,
457 resulting in extremely dry conditions during the 1970s and 1980s; there has been some
458 recovery of the rains since 1990 but totals remain well below the mid-20th century values
459 (Greene et al 2009; Lebel and Ali 2009; Biasutti 2013). Like many regions of the world, the
460 western Sahel has also warmed on the order of 1°C during that time (Niang et al 2014),
461 promoting drought conditions.

462 *3.3.3 Baseline*

463 With a growing population, there has been a large increase in agricultural area in the
464 western Sahel at the expense of wooded vegetation (Brink and Eva 2009; Ruelland et al
465 2011). The growing population may also be harvesting a larger amount of firewood. The
466 basic structure of the agroforestry system and its management by local farmers have been
467 reported to be fairly stable over the period covered here (Maranz 2009).

468 *3.3.4 Impact Detection*

469 Over the past half century there has been a decrease in tree density in the western Sahel
470 noted through field survey as well as aerial and satellite imagery (Vincke et al 2010;
471 Ruelland et al 2011; Gonzalez et al 2012), and by local populations (Wezel and Lykke
472 2006). Because of their sensitivity to moisture deficits, trees would be expected to
473 become less densely spaced during long-term soil-moisture drought. Tree mortality has
474 been more pronounced for introduced or managed fruit-bearing trees, which may be less
475 adapted to decadal-scale drought conditions which appear typical of the western Sahel
476 than the native vegetation (Wezel and Lykke 2006; Maranz 2009).

477

478 The patterns of tree cover changes remain correlated with the combined effects of the
479 warming and drying trends after accounting for the effects of other factors (Gonzalez et al
480 2012). Moreover, the enhanced mortality among introduced species in relation to

481 indigenous species is more consistent with the effect of climate change than with that of
482 the other drivers listed above (Wezel and Lykke 2006; Maranz 2009).

483 *3.3.5 Attribution*

484 The harvesting of firewood does not appear to have played a substantial role in the
485 decrease in tree density (Gonzalez et al 2012). The shift from wooded to agricultural
486 areas is substantial (Brink and Eva 2009; Ruelland et al 2011), and the decreases in tree
487 density are correlated with proximity to human presence (Vincke et al 2010). However,
488 both the warming and decreased rainfall trends appear to have played at least as large a
489 role in the overall decrease in tree density (Gonzalez et al 2012), though this has not been
490 examined specifically for fruit-bearing trees.

491 **3.4 Wildfire in Australia**

492 *3.4.1 Hypothesis*

493 Many high-impact fires occurred over the last decade, amongst them the 2009 “Black
494 Saturday” Bushfires, which were reported as one of the worst natural disasters in the
495 history of Australia, with 173 lives lost, and around 2300 homes plus other structures
496 destroyed (Crompton et al 2010). Bushfires occur naturally in Australia, and many of the
497 influencing parameters are directly (temperature, precipitation and windiness) or
498 indirectly (available fuel, land use and cover, fire history) susceptible to climate change
499 (Williams et al 2009), with fire risk expected to increase under climate change (Reisinger
500 et al 2014, Box 25-6). Hence a possible increase in fire hazard due to recent climate
501 change may have translated into increased damages from wildfire.

502 *3.4.2 Climate trend*

503 Increases in aggregate climate indices such as average temperature, maximum
504 temperatures, and the length of hot-spells have been detected on continental scale, albeit
505 with strong seasonal and regional variations (Alexander and Arblaster 2009; Trewin and
506 Vermont 2010). Composite indices such as the McArthur Forest Fire Danger Index (FFDI)
507 have been developed to capture the combined influence of relevant meteorological
508 variables such as temperature, relative humidity, wind speed and direction and

509 antecedent precipitation for the assessment of fire risk. A trend in the FFDI toward
510 increasing danger has been observed since 1970 over large parts of Australia, especially in
511 the South and South East, with a clear signature of annual and decadal climate modes
512 such as the El Niño/Southern Oscillation and the positive phase of the Indian Ocean
513 Dipole (Mills et al 2008; Clarke et al 2013).

514 *3.4.3 Baseline*

515 Damages from wildfire have increased over the course of the century, consistent with the
516 observed climate trends, but also with the effects of an increased number of exposed
517 assets (such as settlements built in or close to fire prone bush land), and increases in
518 population. Better fire management and improved forecasting may counteract these
519 trends, however their influence has not been quantified (Crompton et al 2011; Nicholls
520 2011).

521 *3.4.4 Impact Detection*

522 No detectable trend has been found in building damages or losses of life normalized
523 against trends in population and number of dwellings over the last century or decades
524 (Crompton and McAneney 2008; McAneney et al 2009; Crompton et al 2010). The
525 normalization process does not account for all factors that influence vulnerability, e.g.
526 human behavior such as precautionary measures of individual home owners, or collective
527 measures of changing spatial planning in order to reduce risk. Several of these factors
528 have been explored in the literature, often with a focus on specific regions or events.

529 Examples include the role of the “prepare, leave early or stay and defend” policy in New
530 South Wales, or the reduction of community vulnerability through improved risk
531 management (Haynes et al 2010; O’Neill and Handmer 2012; Whittaker et al 2013).

532 Damage from extreme fires is mainly controlled by exposure, as structures built in close
533 proximity to or within bush land are virtually impossible to defend during extreme fire
534 conditions (Chen and McAneney 2004). In the Greater Melbourne area, encroachment of
535 suburban dwellings into bush land has led to an increase in the number of exposed
536 dwellings (Butt and Buxton 2009; Buxton et al 2011).

537

538 Crompton et al. (2011) in a reply to Nicholls (2011) discusses and dismisses several factors
539 (incl. improved fire management, forecasting, individual home owners defence measures)
540 that could be masking a trend consistent with a climate signal in the overall loss statistics.
541 They conclude that an influence of anthropogenic climate change “is not ruled out by our
542 analysis, but, if it does exist, it is clearly dwarfed by the magnitude of the societal change
543 and the large year-to-year variation in impacts”. In summary, an impact of climate change
544 on observed damages from bushfires in Australia has not been detected.

545

546 **3.5 Urban coastal erosion and flooding in West Africa**

547 *3.5.1 Hypothesis*

548 Anthropogenic warming of the climate system is expected to cause widespread rises in
549 sea level. West Africa has a number of low-lying urban areas particularly exposed to sea
550 level rise, with increases in coastal erosion and flooding expected (Dossou and
551 Glehouenou-Dossou 2007; Douglas et al 2008; Adelekan 2010).

552 *3.5.2 Climate trends*

553 There has been a lack of sustained tide gauge monitoring in West Africa over the past few
554 decades (Church and White 2011; Fashae and Onafeso 2011). While satellite monitoring
555 suggests rising total sea levels in the Gulf of Guinea, actual relative sea level changes at
556 specific locations along the coast will depend on additional factors, such as human
557 induced subsidence, or natural variations in ocean currents (Stammer et al 2013).

558 *3.5.3 Baseline*

559 The construction of ports has diverted coastal sediment transport around Cotonou, Benin,
560 while marine sand quarries have already reduced the supply of sand to the city (Dossou
561 and Glehouenou-Dossou 2007). Other plausible drivers of increased erosion have also
562 been posited, and include subsidence due to oil exploration for Lagos, Nigeria, and
563 sediment trapping in reservoirs for most of the West African Coast (Ericson et al 2006;
564 Douglas et al 2008).

565 *3.5.4 Impact Detection*

566 Based on photographic evidence and comparison with satellite imagery, coastlines in
567 some urban areas in the Gulf of Guinea seem to have been retreating over the past few
568 decades (Dossou and Glehouenou-Dossou 2007; Fashae and Onafeso 2011). Ericson et al.
569 (2006) found that sediment trapping is the dominant cause of contemporary effective sea
570 level rise for the Niger delta, with contributions from land subsidence due to oil
571 exploration. Also, the construction of reservoirs on the Volta has led to a sharp decrease
572 in sediments moving across the West African coast, passing cities such as Cotonou and
573 Lagos. Given the lack of long-term monitoring of local sea level, coastal erosion, and the
574 various possible drivers of coastal erosion, it is currently not possible to examine whether
575 an anthropogenic climate change signal has been detected.

576 **4 Discussion**

577

578 This paper was motivated by an apparent inconsistency between the accepted view that
579 climate change is already impacting a number of vulnerable human and managed
580 systems, and the relative lack of documented evidence of observed impacts of climate
581 change for those vulnerable systems. There is a large literature concerning the sensitivity
582 of such systems to climate, and to future climate change, but there is comparatively little
583 documentation of observed impacts of climate change (Cramer et al. 2014).

584 A major factor explaining this gap consists in the lack of calibrated long-term monitoring
585 across sensitive systems and regions, which would provide the observational basis that
586 underpins detection and attribution analysis. Under the United Nations Framework
587 Convention on Climate Change (UNFCCC), nations are obligated to monitor their
588 respective contributions to anthropogenic forcing through standardized national
589 greenhouse gas inventories, but no such inventory scheme or standard exists for impacts
590 of climate change.

591

592 Detection and attribution studies are virtually impossible for impacts in some regions due
593 to the absence of an observational basis. For example, to determine how sea level rise
594 might be affecting urban coastal areas in West Africa (see 3.5) the current ambiguity over

595 whether relative sea level has actually risen along the urban coastlines is a hindrance.
596 Innovate methods exist to fill in such gaps, for instance through analysis of archival
597 footage or consulting local and indigenous knowledge, and can provide valuable tools in
598 some cases (Rosenzweig and Neofotis 2013).

599

600 The five examples discussed in Section 3 draw on disparate studies across disciplines for a
601 comprehensive analysis of the role of observed climate change in the changes that various
602 systems have experienced during recent decades. However, they also illustrate some of
603 the challenges involved in the detection and attribution of impacts of climate change. For
604 example, the ecosystem of Lake Victoria faced the introduction of large predatory species,
605 and subsequently a regime shift occurred. Predicting the ecosystem response to such
606 major unprecedented change would be challenging even if the underlying ecosystem
607 dynamics were well understood. While it is plausible to assume that increased
608 precipitation will have contributed to increases in agricultural productivity in Southeast
609 South America, it is very difficult to disentangle the influence of the climate trend from
610 that of technological development and socioeconomic conditions for parts of the region.
611 Similarly, complex factors related to exposure preclude the detection of a climate related
612 signal in damages from bushfire in Australia. In the case of West Africa, the monitoring of
613 all drivers contributing to coastal erosion and flooding, as well as the documentation of
614 the actual changes remains insufficient.

615

616 In some cases though, the examples also point to ways forward. Local knowledge has
617 been valuable in assessing the role of rainfall decreases in the thinning of western
618 Sahelian forests, similar to what has long been documented for Inuit observations of
619 change in the Arctic (e.g., Nichols et al 2004; Krupnik and Ray 2007; Weatherhead et al
620 2010). Sediment cores provide proxy evidence that the current warming of the African
621 Great Lakes is, essentially, unprecedented. Examination of historical aerial and satellite
622 photography provided important insights about the baseline in several of the case studies.
623 The roles of some potential drivers for Australian bushfire damage were elucidated by
624 comparative analyses across fire events, regions, and other dimensions.

625

626 Several examples point to the synergistic effects of changes in climate and other drivers,
627 e.g. the enabling role of the precipitation increases for extension of agricultural activity
628 (3.2), or the role of warming and weakening winds in triggering the ecosystem shift in
629 Lake Victoria (3.1). To adequately capture the role of climate change in the light of other
630 factors that may act as additional stressors, provide resilience, or create synergistic effects
631 different from the effect of any individual driver remains a central challenge for impact
632 attribution.

633

634 A fundamental issue we have only touched upon briefly concerns the end point of
635 attribution studies. For large parts of the community studying climate change and its
636 impacts, as well as many stakeholders, “attribution” is used as a synonym for “attribution
637 to anthropogenic forcing”. As one of the key motivations for detection and attribution
638 research is to inform the UNFCCC, this end-point has often been considered the main goal
639 (Zwiers and Hegerl 2008). It is important in the context of potential litigation for adverse
640 impacts of climate change (Grossman 2003), and may become relevant for the recently
641 established “Warsaw International Mechanism for Loss and Damage” under the UNFCCC
642 (James et al 2014). To assess the relative role of anthropogenic versus natural forcing in
643 observations provides a means to estimate whether recent and current impacts might be
644 expected to persist, and to calibrate predictions of future impacts made with other
645 methods. However, as we have shown, it is often very difficult to detect climate change
646 effects in observed records, and to disentangle the impacts of climate change from those
647 of other drivers of change. Clearly, attribution of observed impacts to anthropogenic
648 climate change adds another layer of complexity to an already challenging exercise.

649

650 Impact attribution research improves the understanding of vulnerabilities to long-term
651 climatic trends, including interactions and non-additive effects of multiple drivers, for
652 which identification of the underlying driver of the observed climate change may not be
653 relevant (Parmesan et al 2011; Parmesan et al 2013). Impact detection and attribution
654 provides important insights from “real world” conditions as compared to experimental
655 conditions or idealized models. Such knowledge is essential to identify the most adequate
656 adaptation strategies and resilient pathways. Given the increasing rate of climate change

657 and possible threshold behaviour in impacted systems, as well as ongoing adaptation and
658 general development, caution must be applied when inferring conclusions about future
659 climate change impacts from observations.

660

661 It is also essential to be clear about the difference between the estimation of sensitivity to
662 weather, and the observation of an impact of climate change. This applies especially with
663 regard to the perception of manifestations of climate variability, such as severe drought or
664 storms. For many human and managed systems, impacts of extreme weather or climate
665 shocks are the rare occasion where a clear climate related signal can be detected.

666 However, while the impact of a particular extreme can be an important indicator of
667 sensitivity to climate it does not by itself constitute a climate change impact (Allen et al
668 2007; Stott et al 2013; Hulme 2014).

669 **5 Conclusions**

670 Detection and attribution of climate change impacts provides the most complete and
671 consistent analysis possible of the cause-effect chain, combining all possible sources of
672 information in a coherent evaluation. While setting a high bar, the distinction between
673 impacts that have been observed in data and linked to climate change with confidence,
674 and those that are predicted to occur but cannot be detected and attributed by science
675 (as yet) has proven a useful distinction. However, caution must be applied both ways
676 when interpreting results. The lack of documented impacts attributable to climate change
677 should not be misread as evidence for the absence of such impacts (Hansen and Cramer
678 2015). On the other hand, it is true that for many historic impacts on human systems,
679 non-climate related drivers are equally or more important than recent climate change,
680 and must be accounted for.

681

682 There may be cases where data are insufficient to detect an impact, while given climate
683 trends and known sensitivity strongly suggests that climate change will have affected the
684 system. While we support the use of different types of evidence, and the application of
685 interdisciplinary methods to establish causality, the fact remains that observational

686 evidence demonstrating a long term effect is needed for impact attribution. Or to put it
687 another way – you can't attribute something you have not detected.

688

689 Detection and attribution analysis can be a powerful tool in understanding how and why
690 our world is changing, albeit its cost is the need to possess the necessary observations
691 and understanding, which remains poor in many areas. To identify those gaps, to
692 determine whether they can be filled, and if so to prioritize research to address them, will
693 lead to a more comprehensive and inclusive understanding of the impacts of climate
694 change.

695

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705

706

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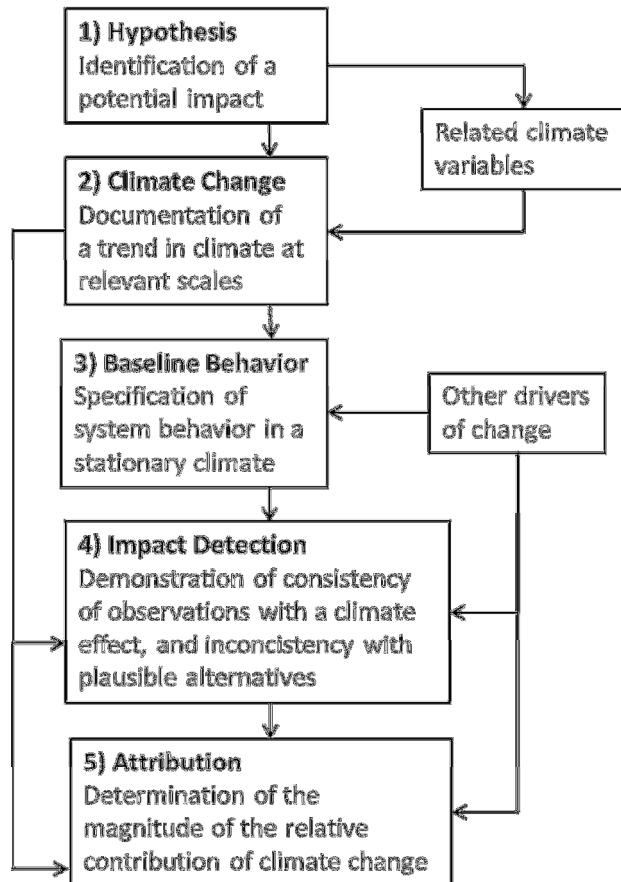
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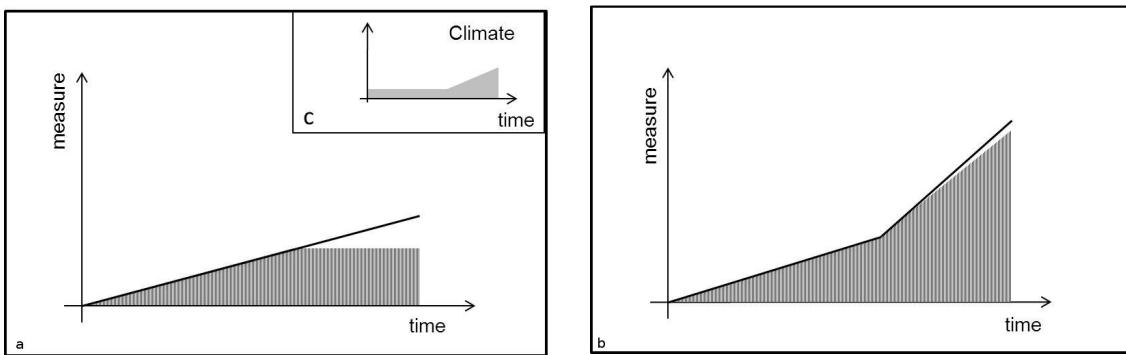
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1009 **Figure 2 Stylized examples of the time series of some measure representing a climate**
1010 **sensitive system which is responding in time to multiple drivers, one of them climate**
1011 **change (the corresponding time series of the climate variable for both cases is shown in**
1012 **panel c). The black line depicts the overall behavior of the system, while the dark,**
1013 **vertically striped area represents the combined effect of non-climate drivers under**
1014 **stationary climatic conditions, and the light area represents the additional effect due to**
1015 **recent climate change. In panel a, the baseline condition (dark area) shows a clear**
1016 **change midway through the record (e.g. due to a policy measure) but this is**
1017 **compensated by the influence of climate change. However the resulting overall measure**
1018 **does not show a deviation from its historical pre-climate change trend, thus masking the**
1019 **existing climate change effect (potential type I error). In panel b, the observed behavior**
1020 **shows a change that is consistent in direction with a predicted climate change impact;**
1021 **however, the majority of that change happens due to a change in the baseline arising**
1022 **from other factors. This situation could lead to erroneous detection (potential type II**
1023 **error) or an overstatement of the climate effect.**