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Multi-proxy analysis: a reflection on essence and potential pitfalls

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Abstract

Multi-disciplinarity and multi-proxy approaches are necessary to understand the processes in complex earth systems. However, unlimited and uncontrolled multi-proxy-correlations may be risky. A number of case studies illustrate the potential pitfalls when the processes that drive the individual proxies have no common causal significance or dating is not precise enough. Crossing thresholds at different levels and delay times may also be factors that hamper direct correlations of proxies. Multi-proxy *analysis* of the intrinsic relationships between proxies in a system is the primary task before any correlation should be made.

Keywords: multi-proxy correlation, proxy

Introduction

Since some time, a criterion in the evaluation of (earth) research projects is their 'multi-disciplinary character'. The apparent argument is that a project with a multi-disciplinary approach is generally considered of greater value than a project applying a single approach. The rationale behind that tendency seems to be the holistic principle that the result is more than the sole sum of the individual parts.

Another tendency is the use of proxies to qualify or estimate the activity and evolution of processes taking place in a specific system or describing the conditions in such a system. At present, it is common practice in many sciences, but is certainly a favorite in earth sciences, where processes and past environmental conditions have to be inferred from geomorphological, geochemical or other palaeo-ecological features (proxies). Essentially, the aim of proxies is not only to recognise but also to explain those processes and conditions. This is the case in a single proxy-to-process (or condition) relation, but is even more valid when several proxies are used to analyze one specific process (or condition). Necessarily, those proxies and their effects have to be mutually correlated in a 'multi-proxy correlation'.

Correlations over long distances are commonly made nowadays. Although warnings against such correlations have been expressed previously, these warnings dealt mostly with specific cases such as correlations of loess records with marine and ice core data (e.g. Singhvi et al., 2001). In this paper, the validity of multi-proxy correlations is discussed in a more general context. Apparently, we need proxies, and therefore it is useful to reflect whether we use the 'multi-proxy approach' in the right way or do so because it is a fashionable trend. By means of a few examples, the essence of using (a multitude of) proxies is discussed and apparent pitfalls are highlighted.

The development of multi-proxy research

The evolution from individual research to team work has been developing persistently and continuously since the beginning of the previous century. Multi-authored papers already exist since some time, but in the beginning, they were only a minority. This is illustrated in Fig. 1, showing a random selection of 730 geomorphological publications since the beginning of the 20th Century, based on the reference lists in Louis (1961) and Huggett (2007), and subdivided according to the number of authors in 4 periods of appearance (prior to 1940, 1940-1960, 1960-1985, 1985-2010). The trend is obvious: almost 99% of the

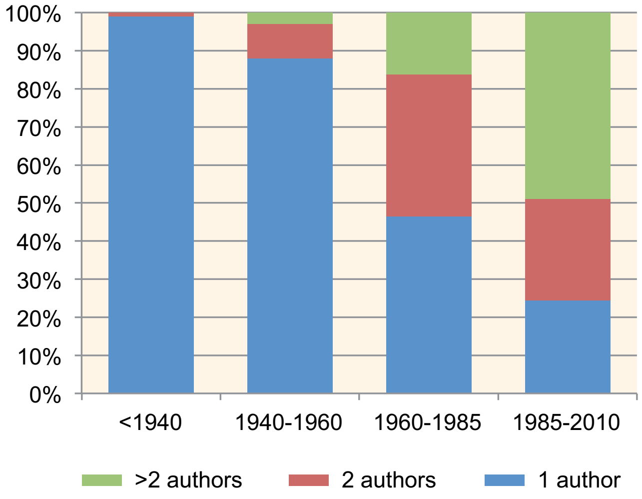

Fig. 1 Percentage of publications as a function of number of authors and time period (prior to 1940, 1940-196, 1960-1985, 1980-2010) as recorded in the reference lists of Louis (1960) and Huggett (2007).

papers before 1940 were single-authored; the first works with more than 2 authors started only after 1940, while nowadays more than 50% of the papers are carried out by more than 2 authors.

The tendency to multi-authored publications reflects in general the increased participation of different disciplines in research. But, what was the reason for including more than one discipline in specific research projects? Each main scientific discipline has become more specialised. Although this development is common in most natural sciences, the main argument in earth science research may be found in the desire to *understand and explain systems* that by nature are complex and thus need an approach from different sides. Such approach has been applied in most earth-scientific or palaeoclimatic research projects since the end of the past century. One of the first examples of an interdisciplinary project was the COHMAP-project (1988), while another illustrative example where this approach was systematically carried out was the EPECC-project on the palaeoclimate of the last interglacial-glacial cycle in Western and Central Europe (Vandenberghe et al., 1998a). At present, the add-on value of a multi-disciplinary or multi-proxy approach has become so evident that it would be unwise to limit ourselves to only one aspect in the study of a particular system.

Understanding the systems, which is the primary objective of multi-disciplinary palaeoclimatic and environmental research, requires *integrating and correlating* the results from the different sources involved. Otherwise, we would have a collection of many mono-disciplinary approaches without interference between each other and we would lose the extra-value of applying different disciplines and proxies. This is the most challenging operation, but also the most difficult one. Therefore, a few examples are given that illustrate potential pitfalls, while discussing the main and essential requirements for a reliable integration and correlation of individual proxies.

Requirements and potential pitfalls in a multi-proxy analysis

Combining proxies that result from different forcing factors

Often, different kinds of proxies are combined. This may involve the risk of comparing apples and oranges. In that respect, the relation between different proxies from different locations is the most problematic one. Of course, objective and initially exploratory comparisons are always allowed. However, a meaningful relation between two spatially separated proxies aiming to explain a certain mechanism in the system can only be established when both these proxies have a common and simultaneous process-relationship.

There are many examples where such relations are postulated, simply assuming there should be one common forcing element acting at the same moment. An example is the correlation of a peak in grain size or geochemical composition of Chinese loess with oceanic Heinrich or Greenland Dansgaard-Oeschger events (e.g. Porter & An, 1995, and many others). It is at least questionable and certainly not proven, that in those cases there is a common steering factor. Correlation of such proxies, which are not bound by an overarching process, is meaningless, or worse, could lead to false conclusions about the processes operating within the system.

This problem may be partially solved when the proxies are from the same location or occur in a single stratigraphical column. But even in that case, we may face similar process-response difficulties as described in the previous example. In fact, different proxies are often reflecting different processes and/or different climatic variables. Moreover, they may possibly be the result of processes taking place at *different times*. This is illustrated by the next examples, again from loess research.

The first example refers to the relation between interglacial paleosols and the grain-size distribution of loess deposited during those interglacials on the Chinese Loess Plateau (Nugteren et al., 2004). The paleosols are the expression of past climate conditions that took place **after** the deposition of the (fine-grained) loess. Therefore, it is not surprising that the paleosol and grain-size boundaries within such a sedimentary section often do **not** coincide. This is illustrated for the lower boundary of the last-interglacial S1 paleosol at Luochuan, as expressed by its leached $CaCO_3$, high clay content and dark color, which occurs 0.8 m higher than the lower boundary of the interglacial fine-grained loess as expressed by mean and modal values (Fig. 2). This difference is not trivial since it represents about 17,000 years according to the time scale of Nugteren et al. (2004). This example shows that there is not only a problem of different timing of the signals registered in the proxies, but also of different forcing factors: summer monsoon for the soil formation and winter monsoon for the grain size (Vandenberghe et al., 1997).

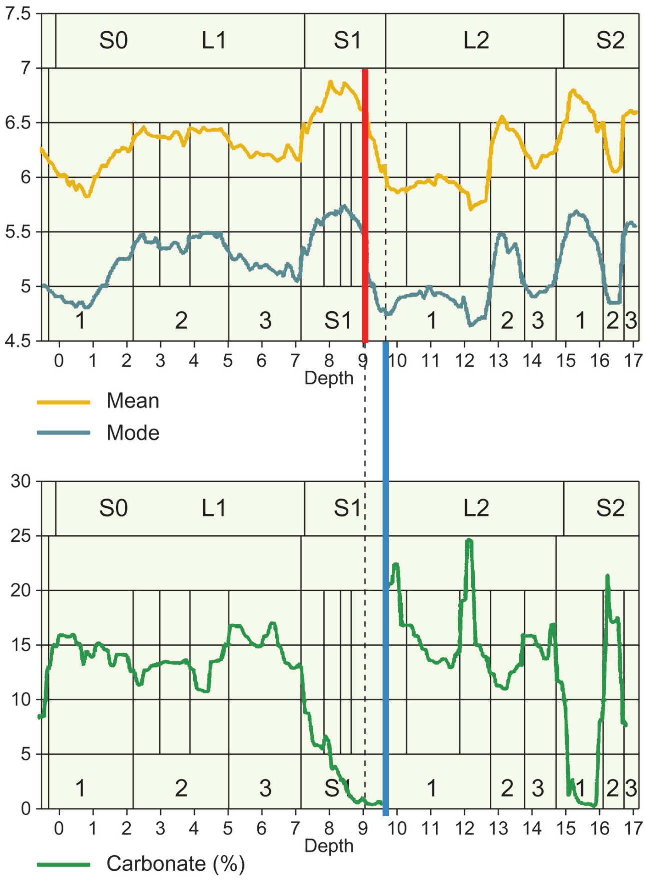

Fig. 2 Comparison of grain size (as indicator of winter monsoon intensity) and % of $CaCO_3$ (expressing soil formation or summer monsoon activity) in the last-interglacial paleosol of the Luochuan loess section (Loess Plateau, China). The red line marks the bottom of the interglacial fine-grained loess, while the blue line marks the bottom of the interglacial soil as evidenced by the $CaCO_3$ leaching.

The second example is from the Kesselt site in the loess belt of temperate Western Europe (Vandenberghe et al., 1998b). A stadial/interstadial alternation is evident from the succession starting with ice-wedge formation and relatively coarse-grained loess deposition during the stadial period (phase 1 in Fig. 3; Vandenberghe & Nugteren, 2001). Subsequently, ice-wedge casting and cryoturbation took place when permafrost decayed at the beginning of the following interstadial (phases 2 and 3 in Fig. 3). At that same time, the grain size of the loess decreased. Ultimately, a hydromorphic tundra-like gleyisol formed during the full interstadial showing an abundance of snails and increased organic content (phase 4 in Fig. 3). The problem here is where to put the start of the interstadial in the sedimentary sequence: is it at the top of the ice-wedge cast, at the top of the cryoturbations coinciding with the decrease in grain size, or at the base of the hydromorphic paleosol? The answer is important for determining the age of the interstadial (for instance by OSL-dating of the loess). Since the ice wedge was formed below the permafrost table, this is at a certain depth below the surface, the top of the ice-wedge cast is situated within the 'cold' loess. Similarly, the base of the paleosol is not a reliable marker for reasons explained in the first example. And thus the shift to a decreased grain-size, together with the top of the cryoturbations that took place in the thickening active layer just below the surface, indicates the best position of the start of the interstadial in the sedimentary record.

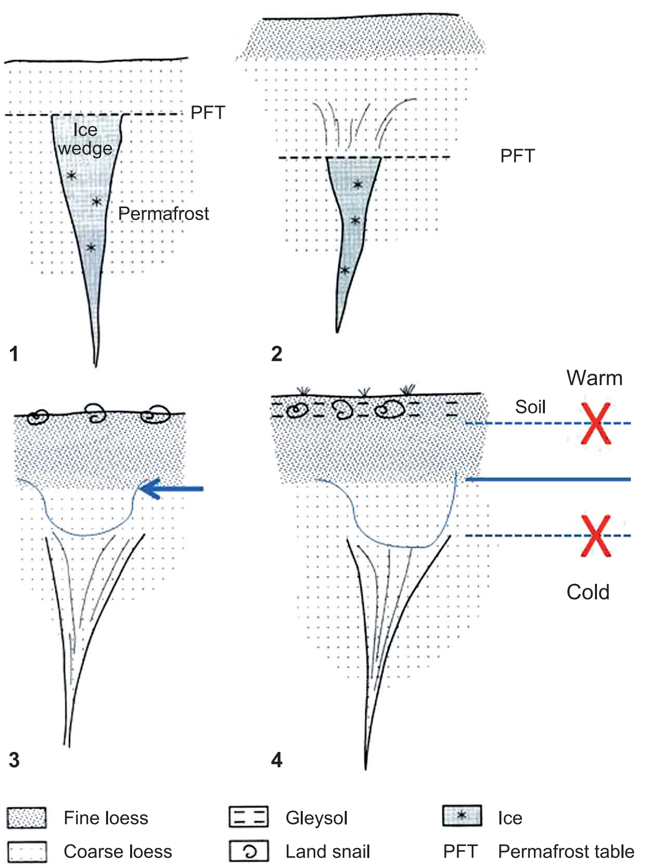

Fig. 3 Succession of loess deposition, permafrost development, permafrost decay and hydromorphic soil formation during a transition from very cold to less cold conditions in four phases, as exemplified in a loess section at Kesselt (Belgium) (modified after Vandenberghe & Nugteren, 2001).

The role of thresholds

Proxies have to cross a definite threshold to actually show a response to a specific external forcing. But, not all proxies necessarily cross threshold values as a response to one and the same external forcing. For instance, the climatic fluctuations during the Weichselian Middle Pleniglacial have been recorded by several terrestrial proxies. However, the magnitude and/or duration of the fluctuations were apparently insufficient to record a signal in the fluvial morphology and sedimentation, at least as recorded in NW Europe (Van Huissteden & Kasse, 2001; Van Huissteden et al., 2001; Lewin & Gibbard, 2010). A fundamental test to illustrate the different reactions of proxies to specific climatic events is described by Bokhorst and Vandenberghe (2009). At two sections near to each other (Titel and Mosorin) the same three paleo-climatic proxies were measured (Ba/Sr ratio, magnetic susceptibility and grain size) reflecting in general temperature, humidity and wind circulation (Fig. 4). The two last-glacial sections were stratigraphically correlated by means of a number of absolute dates (OSL). As appears from Fig. 4 a specific signal was often not picked up by all three proxies in one section and was picked up even more rarely by all three proxies in both sections. This means that different proxies, probably from different environments, did not respond to an external impetus in the same way and multi-proxy comparisons rather than single proxies are able to separate local from regional or global signals. In addition, regional signals may be disturbed by local effects (or noise) as was also found by Vriend (2007) in Chinese loess.

As no unique response is found at the same time in all proxy records in Fig. 4, it may be concluded that there is probably no external forcing that is able to initiate a signal to be recorded in all proxies at all locations and exceeding local noise or internal variability. This may also explain why short-time events in certain proxies seem to coincide with D-O events at one spot, but not at another one nearby (e.g. the multi-proxy records at Les Échets and the Mediterranean region (Sanchez-Goni et al., 2002; Wohlfarth et al., 2008) and some loess records of the Titel Plateau in Serbia (Antoine et al., 2009; Bokhorst et al., 2009). It may be stressed again that understanding the mechanism of the forcing factor is a prerequisite to make reliable correlations of different proxies from different locations. Understanding the passing of tipping points is even more important when assessing the future climate state (Lenton et al., 2008; Lenton, 2011).

The influence of response time

Proxies do not always react immediately to external forcing, because response times may be different. A good example is the delayed reaction of vegetation to climate change. This offset makes it difficult to link vegetation changes directly to climatic changes. In NW Europe, vegetation developed gradually during the Weichselian Late Glacial and at the beginning of the Holocene while, in contrast, the triggering climate change was abrupt at the beginning of both these phases (Hoek, 1997). Apart from these correlation problems, the delayed response of vegetation is the principal reason for river incision in the initial phases of both temperate and cold periods (Vandenberghe, 1993, 1995). As these phases of incision are not linearly coupled to climate change, correlation between incision, as a geomorphological proxy, and climate change, as the forcing factor, should take into account the delay between proxy and forcing factor.

Similar delays are typical in soil formation as mentioned above in the loess-palaeosol cases. In addition, terrestrial records may face the problem of sedimentary hiatuses and preservation potential (Singhvi, 2011). Also, magnetisation needs some time to establish resulting in a different age of the sediment deposition and the posterior magnetisation of that sediment (Zhou & Shackleton, 1999).

Fluvial adaptation was also hardly detected in western Europe during stadial-interstadial transitions, such as the Hasselo-Hengelo interval (Van Huissteden, 1990). Such an interval was often too short for recording a fluvial reaction taking typically

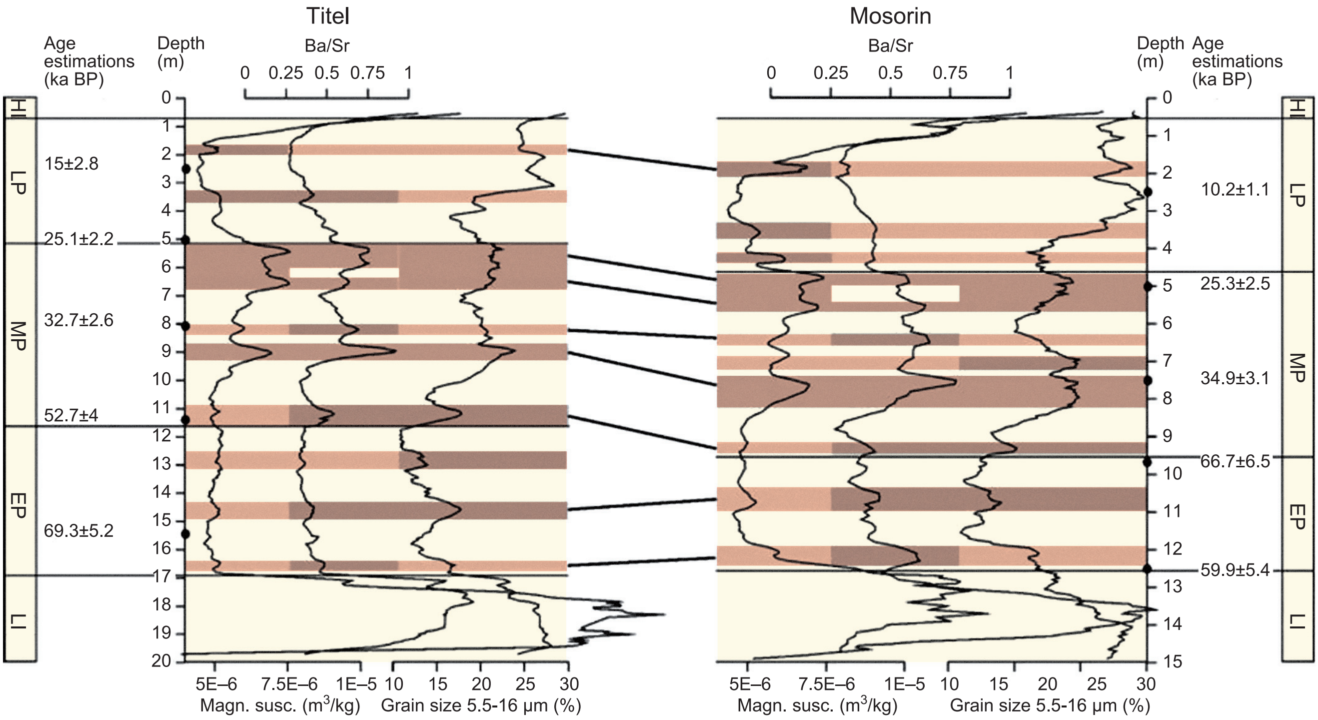

Fig. 4 Potential correlations of different paleo-climatic proxies (reflecting temperature, humidity and wind circulation) at 2 loess sections on the Titel Plateau (Serbia). Coloured bars indicate peaks in proxy values. LP = Late Pleniglacial, MP = Middle Pleniglacial, EP = Early Pleniglacial, LI = Last Interglacial. Reproduced from Bokhorst & Vandenberghe (2009) with permission from Wiley Publ.

some 500-1000 years (Vandenberghe, 2002). Furthermore, the magnitude may have been too low to cross the threshold for reaction (see previous paragraph).

The temporal link

A preliminary requirement of all proxy-correlations is that one can rely on the correct positioning of the individual proxy records on the time axis. For correlation of signals from the same stratigraphical column, this requirement is automatically fulfilled. Correlation over some distance, however, needs independent absolute dating. At first, a date must be sufficiently precise in the records to be correlated. For instance, if a certain record is correlated with D-O or Heinrich events, the ages of that record must have a precision in the order of hundreds (or tens) of years, which is the duration of the shifts associated with those events. Illustrative is – apart from objections discussed above – the correlation of loess grain-size records on the Chinese Loess Plateau with Heinrich events identified in the North Atlantic and GRIP ice core. Porter and An (1995) correlated these records on the basis of thermoluminescence dates from the loess sections with an error bar of ±3 to 7 kyr. Even for very frequently and absolutely dated records, such as the lacustrine series at Les Échets (France), chronological uncertainty is too high to infer correlations between the events in that record and D-O events in Greenland (Wohlfarth et al., 2008; Blaauw et al., 2010a). Finally, precise and reliable ages are an absolute requirement for the determination of leads and lags.

A second problem is that of tuning, often applied in proxy correlation and extensively discussed by Blaauw (2010). In the tuning procedure, it is generally postulated that changes in the proxy records should have been produced by climate changes synchronously and over (very) wide areas. Circular reasoning is, however, an obvious risk since the results from the correlation are essentially also those that were used for the tuning. This plays a role especially at relatively short timescales (centennial-millennial), although less at the glacial-interglacial scale (Blaauw, 2010). Nevertheless, also correlation by tuning and subjective curve matching at glacial-interglacial scale is not without risks (Bogota et al., 2011). Many terrestrial climate events were tuned with D-O cycles in Greenland and thus cannot be used to deduce synchronicity (Blaauw et al., 2010a). In addition, the signal in proxy records decreases with increasing distance from the signal's source (e.g. the ocean), as exemplified by the model-based analysis of the spatial and temporal variation of a cooling signal by Wiersma et al., (2011). Blaauw et al. (2010a) and Singhvi et al. (2001) propose correlations should be based on independent, non-tuned timescales to avoid a kind of 'reinforcement syndrome'.

A third temporal problem in proxy-correlation arises from the question whether processes leading to different proxy signals were indeed contemporaneous. To illustrate this problem, we may consider the extremely well dated loess record at Nussloch (Antoine et al., 2001; Rousseau et al., 2002) showing a remarkable coincidence of radiocarbon dates of organic material in the paleosols and OSL-dates of the loess. As mentioned above, soil formation is a post-sedimentary process. It can be argued that – within the precision limits of the dates – the organic production should have started already during the deposition of the loess. But this was contradicted recently by Gocke et al. (2010) who found that the organic material in those paleosols is post-sedimentary and derived from roots of Holocene age. If this is correct, the remarkable similarity between loess and paleosol ages remains unexplained. In general, uncertainty about the real age of paleosols in loess hampers correlations with the OSL-dated loess in which the soils were formed and with marine and ice records (e.g. Porter & An, 1995; Rousseau et al., 2002; Haesaerts et al., 2009).

Discussion: the causal relationship

The problems discussed in the previous sections are commonly and primordially a consequence of insufficient identifying and understanding the climatic, sedimentological, geomorphological, pedological or periglacial processes involved in the proxy signals, and the spatial extent and precise age of those processes. For instance, one cannot place cryoturbation events in their right stratigraphical frame without knowing the mechanism of cryoturbation. A similar argumentation holds for vegetation development and soil formation. In this respect, it is of utmost importance to evaluate the contribution of intrinsic factors (noise) when assessing overarching external forcing. Finally, attributing one specific causal mechanism to a certain proxy record may be too simple, for instance assuming climate to be the cause of variations in loess grain size when also other causes of continental (e.g. tectonics) to local extent may play an equally important role (Hartman et al., 2011).

The crucial question in correlation proxies is: is there a process or event that explains comparable signals in different and spatially separated proxy records? When a definite link is made, for instance, between loess grain size in China and the oxygen isotope ratio in a North Atlantic marine record this implies that both parameters are an answer to a common causal mechanism, in this case a climatic forcing. The examples given above show that processes acting in a system and their responses, as expressed by individual proxies, may be complex. However, insight is required in the causal pathways within the system to find the right forcing mechanism for each of the proxies, avoiding the effects from random bias and intrinsic factors (Williams et al., 2011). If not, the relationship and correlation remain only a conceptual, although possibly logical, myth or hypothesis. In this respect, physical models may be very useful to increase that insight, especially by investigating whether a particular causal mechanism could explain a certain proxy signal or not. Proxy coincidence (various proxies showing apparently comparable signals or patterns) does not mean per se that there is a common forcing factor for these proxies. Bear in mind the famous 'stork enigma', claiming that babies are delivered by storks since the decreasing number of storks coincides with decreasing births of babies.

The issue of causal inference within a system is not unique for the earth system. It is very common, for instance, in the medical and pharmacological world where relations are searched between potential causal factors (e.g. treatment) and outcomes. Their complex mathematical and statistical models have contributed substantially to identify 'confounding' mechanisms or parameters. But even in that world it is they stated that 'the abstract level of thinking needed and assumptions involved have an added dimension beyond standard statistical association analysis' (Goetghebeur, 2011). Similarly, Blaauw et al. (2010b) reproduced events and trends in palaeo-ecological records by random simulations. In climate modeling, similar 'what if' techniques are applied in scenario studies, but can also be useful elsewhere. Unraveling the complexity in the system dynamics is the challenge for future research, a challenge, which is only achievable by multi-disciplinary research, involving not only proxy and dating expertise but also process expertise.

Conclusions

Since earth systems are obviously very complex, an integrated approach is necessary. This involves the use of many proxies that have to be correlated and inter-related. The extra value of using an integrated approach can only be reached by understanding the processes in the concerned climatic, geomorphological, sedimentological or ecological system, linking the different components of the system. This must precede any correlation.

Furthermore, the general strategy to avoid false correlations and interpretations introduced by confounding factors within a system must include defining and dating the exact stratigraphic position and recognising that proxies cross specific threshold response values with a potential delay.

Finally, in order to express the importance of analyzing the different (sub)systems in terms of the processes going on in them rather than purely 'correlating peak-by-peak', we better use the abbreviation MPA for 'multi-proxy **analysis**' instead of 'multi-proxy approach'.

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