Meta-analysis and its application in global change research

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Meta-analysis is a quantitative synthetic research method that statistically integrates results from individual studies to find common trends and differences. With increasing concern over global change, meta-analysis has been rapidly adopted in global change research. Here, we introduce the methodologies, advantages and disadvantages of meta-analysis, and review its application in global climate change research, including the responses of ecosystems to global warming and rising CO2 and O3 concentrations, the effects of land use and management on climate change and the effects of disturbances on biogeochemistry cycles of ecosystem. Despite limitation and potential misapplication, meta-analysis has been demonstrated to be a much better tool than traditional narrative review in synthesizing results from multiple studies. Several methodological developments for research synthesis have not yet been widely used in global climate change researches such as cumulative meta-analysis and sensitivity analysis. It is necessary to update the results of meta-analysis on a given topic at regular intervals by including newly published studies. Emphasis should be put on multi-factor interaction and long-term experiments. There is great potential to apply meta-analysis to global climate change research in China because research and observation networks have been established (e.g. ChinaFlux and CERN), which create the need for combining these data and results to provide support for governments’ decision making on climate change. It is expected that meta-analysis will be widely adopted in future climate change research.

Climate change has been one of the greatest challenges to sustainable development. Global average temperature has increased by approximately 0.6°C over the past 100 years and is projected to continue to rise at a rapid rate; global atmospheric carbon dioxide (CO2) concentration has risen by nearly 38% since the pre-industrial period and will surpass 700 umol/mol by the end of this century11. Most of the warming over the last 50 years is attributable to human activities, and human influences are expected to continue to change atmospheric composition throughout the 21st century. Climate change has the potential to alter ecosystem structure (plant height and species composition) and functions (photosynthesis and respiration, carbon assimilation and biogeochemistry cycle). The change in ecosystem is expected to alter global climate through feedback mechanisms, which will have effects on human activities and these feedback mechanisms as well. Therefore, climate change, human influences and ecosystem response have become more and more interconnected. However, these

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direct and indirect effects on ecosystems and climate change are likely to be complex and highly vary in time and space\cite{2}. Results from many individual studies showed considerable variation in response to climate change and human activities. Given the scope and variability of these trends, global patterns may be much more important than individual studies when assessing the effects of global change\cite{13,14}. There is a clear need to quantitatively synthesize existing results on ecosystems and their responses to global change and land use management in order to either reach the general consensus or summarize the difference. Meta-analysis refers to a technique to statistically synthesize individual studies\cite{15}, which has now become a useful research method\cite{16} in global change research.

Since Gene Glass\cite{17} invented the term “meta-analysis”, it has been widely applied and developed in the fields of psychology, sociology, education, economics and medical science. It was adapted in ecology and evolutionary biology at the beginning of the 1990s\cite{21}. Earlier introduction and review of the use of meta-analysis in ecology and evolutionary biology were given by Gurevitch et al.\cite{9} and Arnqvist et al.\cite{10}. In 1999, a special issue on meta-analysis application in ecology was published in Ecology, which systematically discussed case studies, development and problems on its use in ecology\cite{11}. In China, meta-analysis has been widely applied in medical science since Zhao et al.\cite{12} firstly introduced meta-analysis into this field. It was mainly used to synthesize the data on control and treatment experiments to determine average effect and magnitude of treatments effects and find the variance among individual studies. Peng et al.\cite{13} were the first to introduce meta-analysis into ecology in China and provided a review on its application in ecology and medical science\cite{14} in recent years.

Meta-analysis has been increasingly applied in large-scale global change ecology in recent years and shows high value on studying some popular research issues related with global change such as the response of terrestrial ecosystem to elevated CO2 and global warming. Unfortunately, there are very few reports available on the use of meta-analysis to examine global climate change in China\cite{15,16}. This paper reviews the general methodology of meta-analysis, assesses its advantages and disadvantages, synthesizes its use in global climate change and discusses future direction and potential application.

1 Meta-analysis method

1.1 Principles and steps

Researches very rarely generate identical answers to the same questions. It is necessary to synthesize the results from multiple studies to reach a general conclusion and find the difference and further direction. Meta-analysis is such a method. The term “meta-analysis” was coined in 1976 by the psychologist Glass\cite{21} who defined it as the statistical analysis of a large collection of analytical results for the purpose of integrating the findings. It is considered as a quantitative statistical method to synthesize multiple independent studies with related hypothesis. “Meta” is from the Greek for “after”. Meta-analysis was translated into different Chinese terms in different fields. Traditionally, reviewing has been done by narrative reviews, where results are easily affected by subjective decision and preference. Meta-analysis allows one to quantitatively combine the results from individual studies to draw general conclusions and find their differences and the corresponding reasons. It is also called “analysis of analysis”.

The steps of performing meta-analysis follow the framework of scientific research: formulating research question, collecting and evaluating data analyzing the data, and interpreting the results. Figure 1 presents the systematic review process\cite{5,6,17}: (i) Research question or hypothesis formulation. For example, how does temperature increase affect tree growth? (ii) Collection of data from individual studies related to the problem or hypothesis. It is desirable to include all of relevant researches (journals, conference proceedings, thesis and reports, etc.). Criteria for inclusion of studies in the review and assessment of studies quality should be explicitly documented. (iii) Data organization and classification. Special forms for recording information extracted from selected literatures should be designed, which include basic study methods, study design, measurement results and publication sources, etc. (iv) Selection of effect size metrics and analysis models. Effect size is essential to meta-analysis. We use the effect size to average and standardize results from individual studies. It quantifies the magnitude of standardized difference between a treatment and control condition. An appropriate effect size measure should be chosen according to the data available from the primary studies and their meanings\cite{5,8,17}. Heterogeneity test should be done to determine the consistence of the results across studies. Statis-
tical models (fixed-effects models, random-effects models and mixed effects models) can also be used. (v) Conduct of summary analyses and interpretation. Individual effect sizes are averaged in a weighted way. Therefore, total average effect and its confidential interval are produced and showed directly as a forest plot (Figure 2) to determine whether there is evidence for the hypothesis. The source of heterogeneity and its impacts on averaged effect size should be discussed. If some factors had great influences on the effect size, quantitative pooling would be conducted separately for each subgroup of the studies. Diagnosis and control of publication bias and sensitive analysis should be also performed.

Figure 2  Effect sizes and their confidential intervals of the effect of land use changes on soil carbon\[18\].

1.2 Advantages and disadvantages

As a new method, exact procedure and methodologies of meta-analysis are being developed\[9,19,20\]. While traditional reviewing done by the narrative reviews can provide useful summaries of the knowledge in a discipline that can be largely subjective, it may not give quantitative synthesis information. It is difficult to answer some complex questions, such as how large is the overall effect? Is it significant? What is the reason attributable to the inconsistence of the results from individual studies?\[8\]. However, meta-analysis provides a means of quantitatively integrating results to produce the average effect, it improves the statistical ability to test hypotheses by pooling a number of datasets\[17,21\]. It can be used to develop general conclusions, delimit the differences among multiple studies and the gap in previous studies, and provide the new research directions and insights.

Criticisms of meta-analysis are due to its shortcomings and misapplications\[17,21\], including publication bias, subjectivity in literature selection and non-independence among studies. Publication bias is defined as bias due to the influence of research findings on submission, review and editorial decisions, and may arise from bias at any of the three phases of the publication process\[22,23\]. For example, studies with significant treatment effects results tend to be published more easily than those without treatment effects. Various methods are developed to verify the publication bias\[24–28\]. When bias is detected, further analysis and interpretation should only be carried out with caution\[19\].

1.3 Special software

Many software packages for performing meta-analysis
have been developed (http://www.um.es/facpsi/metaanalysis/software.php), some of which are listed in Table 1. Besides special meta-analysis software, general statistical software packages such as SAS and STAT also have standard meta-analysis functions. These programs differ in the data input format, the measures of effect sizes, statistical models, figures drawing and whether some functions such as cumulative meta-analysis and sensitive analysis should be included. Of all the mentioned software, CMA, MetaWin, RevMan and WeasyMA have user-friendly interfaces and powerful functions covering calculation of effect sizes, fixed-effect and random-effect models, heterogeneity test, subgroup analysis, publication bias analysis, cumulative meta-analysis and meta-regression. MetaWin provides non-parameter tests and statistic conversions. CMA gives the function for sensitivity analysis. After conducting online literature search for which meta-analysis software packages were most commonly used in published journal papers from Elsevier, Springer and Blackwell publishers, we found that the most frequently used packages are RevMan (270 papers), MetaWin (80 papers) and DSTAT (60 papers).

2 Case studies of meta-analysis in global climate changes

Since the first research on meta-analysis conducted in global climate change,[29] meta-analysis has been increasingly utilized in this field. Figure 3 presents the number of publications from 1996 to 2005 that used meta-analysis for global climate change research. It shows an increasing trend in general.

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2.1 Response of ecosystem to elevated CO$_2$

It is recognized that CO$_2$ concentration in the atmosphere and global temperature are increasing. CO$_2$ is not only one of the main gases responsible for the greenhouse effect, but an essential component for photosynthesis, plant growth and ecosystem productivity as well. Increasing CO$_2$ concentration results in rising temperature which alters carbon cycle of terrestrial ecosystem. Response of ecosystem to elevated CO$_2$ is important to global carbon cycle[30,31] and is an essential research issue in ecology and climate change research. Research using meta-analysis has addressed some ecological processes and relationships, including plant photosynthesis and respiration, growth and competition, productivity, leaf gas exchange and conductance, soil respiration, accumulation of soil carbon and nitrogen, the relations between light environment and growth, and photosynthesis and leaf nitrogen.

The effect of elevated CO$_2$ on plant growth is generally positive. Curtis et al.[32] used meta-analytical methods to summarize and interpret more than 500 reports of effects of elevated CO$_2$ on woody plant biomass accumulation. They found total plant biomass significantly increased by 28.8% and the responses to elevated CO$_2$ were strongly affected by environmental stress factors and to a less degree by duration of CO$_2$ exposure and functional groups. In another study on the response of C$_3$ and C$_4$ plants to elevated CO$_2$, Wand et al.[33] used mixed-effect model for meta-analysis to show that total biomass has increased by 33% and 44% in elevated CO$_2$ for both C$_3$ and C$_4$ plants, respectively. These authors also found C$_3$ and C$_4$ plants have different morphologi-
cal developments under elevated CO$_2$. C$_3$ plants developed more tillers and increased slightly in leaf area. By contrast, C$_4$ plants increased in leaf area with slight increase in tiller numbers. A significant decrease in leaf stomatal conductance, as well as increased water use efficiency and carbon assimilation rate were also detected. These results have important implications for the water balance of important catchments and rangelands, particularly in sub-tropical and temperate regions. Their study also implied that it might be premature to predict that the C$_4$ type will lose its competitive advantage in certain regions as CO$_2$ levels rise, based only on different photosynthetic mechanisms. Environmental factors (soil water deficit, low soil nitrogen, high temperature and high concentration O$_2$) significantly affected the response of plants to elevated CO$_2$. The total biomass has increased by 30.01% for C$_3$ plants under unstressed condition. Kerstiens used meta-analysis to test the hypothesis that variation of growth responses of different tree species to elevated CO$_2$ was associated with the species’ shade-tolerance. This study showed that in general, relatively more shade-tolerant species experienced greater stimulation of relative growth rate by elevated CO$_2$. Pooter et al. evaluated the effects of increased atmospheric CO$_2$ concentrations on vegetation growth and competitive performance using meta-analysis. They detected that the biomass enhancement ratio of individually grown plants varied substantially across experiments and that both species and size variability in the experimental populations was a vital factor. Responses of fast-growing herbaceous C$_3$ species were much stronger than those of slow-growing C$_3$ herbs and C$_4$ plants. CAM species and woody plants showed intermediate responses. However, these responses are different when plants are growing under competition. Therefore, biomass enhancement ratio values obtained for isolated plants cannot be used to estimate those of the same species growing in interspecific competition.

Meta-analysis was also performed to summarize a suite of photosynthesis model parameters obtained from 15 field-based elevated CO$_2$ experiments of European forest tree species. It indicated a significant increase in photosynthesis and a down-regulation of photosynthesis of the order of 10\% to 20\% to elevated CO$_2$. There were significant differences in the response of stomata to elevated CO$_2$ between different functional groups (conifer and deciduous), experimental durations, and tree ages. Ainsworth et al. made the first meta-analysis of 25 variables describing physiology, growth and yield of single crop species (soybean). The study supported that the rates of acclimation of photosynthesis were less in nitrogen-fixing plants and stimulation of photosynthesis of nitrogen-fixing plants was significantly higher than that of non-nitrogen-fixing plants. Pot size significantly affected these trends. Biomass allocation was not affected by elevated CO$_2$ when plant size and ontogeny were considered. This was consistent with previous studies. Again, pot size significantly affected carbon assimilation, which demonstrated the importance of field studies on plant response to global change. While experiments on plant response to elevated CO$_2$ provide the basis for improving our knowledge about the response, most of individual species in these experiments were from controlled environments or enclosure. These studies had some serious potential limitations, for example, enclosures may amplify the down-regulation of photosynthesis and production. FACE (Free Air CO$_2$ Enrichment) experiments allow people to study the response of plants and ecosystems to elevated CO$_2$ under natural and fully open-air conditions. In the meta-analysis of physiology and production data in the 12 large-scale FACE experiments across four continents, several results from previous chamber experiments were confirmed by FACE studies. For example, light-saturated carbon uptake, diurnal carbon assimilation, growth and above-ground production increased, while specific leaf area and stomatal conductance decreased in elevated CO$_2$. Different results showed that trees were more responsive than herbaceous species to elevated CO$_2$ and grain crop yield increased far less than anticipated from prior enclosure studies. The results from this analysis may provide the most plausible estimates of how plants growing in native environments and field will respond to elevated CO$_2$. Long et al. also reported that average light-saturated photosynthesis rate and production in-
creased by 34% and 20% respectively in C₃ species. There was little change in capacity for ribulose-1,5-bisphosphate regeneration and little or no effect on photosynthetic rate under elevated CO₂. These results differ from enclosure studies.

Meta-analysis of the response of carbon and nitrogen in plant and soil to rising atmospheric CO₂ revealed that averaged carbon pool sizes in shoot, root, and whole plant have increased by 22.4%, 31.6%, and 23.0%, respectively, and nitrogen pool sizes in shoot, root, and whole plant increased by 4.6%, 10.0%, and 10.2%, respectively [41]. The high variability in CO₂-induced changes in carbon and nitrogen pool sizes among different CO₂ facilities, ecosystem types and nitrogen treatments resulted from diverse responses of various carbon and nitrogen processes to elevated CO₂. Therefore, the mechanism between carbon and nitrogen cycles and their interaction must be considered when we predict carbon sequestration under future global change.

The response of stomata to environment conditions and controlled photosynthesis and respiration is a key determinant of plant growth and water use [42]. It is widely recognized that increased CO₂ will cause reduced stomatal conductance, although this response is variable. For example, Curtis et al. [43] reported that stomatal conductance decreased by 11%, not significantly under elevated CO₂. In the meta-analysis on data collected from 13 long-term (>1 year), field-based studies of the effects of elevated CO₂ on European tree species [43], a significant decrease of 21% in stomatal conductance was detected, but no evidence of acclimation of stomatal conductance was found. The responses of young, deciduous and water stressed trees were even stronger than in older, coniferous and nutrient stressed trees. Using the data from Curtis et al. [43], Medlyn et al. [44] found that there was no significant difference in terms of the CO₂ effect on stomatal conductance between pot-grown and freely rooted plants, but there was a difference between short-term and long-term studies. Short-term experiments of less than one year showed no reduction in stomatal conductance; however, longer-term experiments (> 1 year) showed 23% decrease. Compared with previous studies [36], these responses under long-term experiments were much more consistent. Thus, long-term experiments are essential to the studies of the response of stomatal conductance to elevated CO₂. Other meta-analysis studies also support the results of the reduction of leaf area and stomatal conductance under elevated CO₂ [16,39,40].

Leaf dark respiration is a very important component of the global carbon budget. The response of leaf dark respiration and nitrogen to elevated CO₂ was studied by meta-analysis, which demonstrates a significant decrease [29,32]. In a meta-analytical test of elevated CO₂ effects on plant respiration [44], mass-based leaf dark respiration (R_d) was significantly reduced by 18%, while area-based leaf dark respiration (R_d) marginally increased approximately 8% under elevated CO₂. There were also significant differences in the CO₂ effects on leaf dark respiration between functional groups. For example, leaf R_d of herbaceous species increased, but leaf R_d of woody species did not change. Their meta-analysis reported increasing carbon loss through leaf R_d under a higher CO₂ environment and a strong dependency of R_d responses to elevated CO₂ under experimental conditions.

It is critical to understand the effects of elevated CO₂ on leaf area index (LAI) [45]. However, no consistent results have been reported [46,47]. Meta-analysis of soybean studies showed that the averaged LAI increased by 18% under elevated CO₂ [47], however, no significant increase was found in the meta-analysis of FACE experimental data [40].

The relationship between photosynthetic rate and leaf nitrogen content is an important component of photosynthesis models. Meta-analysis combining with regression is able to assess whether the relationship was more similar to species within a community than between community and vegetation types, and how elevated CO₂ affected the relationship [48]. Approximately 50% community and vegetation types had similar relationship between photosynthetic rate and leaf nitrogen content under ambient CO₂. There were also differences of CO₂ effects on the relationship between species.

Reproductive traits are the key to investigate the response of communities and ecosystems to global change. Jablonski et al. [49] conducted the first meta-analysis of plant reproductive response to elevated CO₂. They found that across all species, CO₂ enrichment resulted in the increase of flowers, fruits, seeds, individual seed mass and total seed mass by 19%, 18%, 16%, 4% and 25%, respectively, and the decrease of seed nitrogen concentration by 14%. There were no differences between crops and wild species in terms of total mass response to elevated CO₂, but crops allocated more mass to reproduction and produced more fruits and seeds than wild spe-
cies did when they grew under elevated CO$_2$. Seed nitrogen in legumes was not affected by elevated CO$_2$ concentrations, but declined significantly for most nonlegumes. These results indicated important differences in reproductive traits between individual taxa and functional groups, for example, crops were much more responsive to elevated CO$_2$ than wild species. The effects of variation of CO$_2$ on reproductive effort and the substantial decline in seed nitrogen across species and functional groups had broad implications for function of natural and agro-ecosystems in the future.

Soil carbon is an essential pool of global carbon cycle. Using meta-analysis techniques, Jastrow et al.\[59\] showed a 5.6% increase in soil carbon over 2—9 years, at rising atmospheric CO$_2$ concentrations. Luo et al.\[41\] also demonstrated that averaged litter and soil carbon pool sizes at elevated CO$_2$ were 20.6% and 5.6% higher than those at ambient CO$_2$. Soil respiration is a key component of terrestrial ecosystem carbon processes. Partitioning soil CO$_2$ efflux into autotrophic and heterotrophic components has received considerable attention, as these components use different carbon sources and have different contributions to overall soil respiration\[51,52\]. The results from partitioning studies by means of a meta-analysis indicated an overall decline in the ratio of heterotrophic component to soil carbon dioxide efflux for increasing annual soil carbon dioxide efflux\[53\]. The ratios of boreal coniferous forests were significantly higher than those of temperate, while both temperate and tropical latifoliate forests did not differ in ratios from any other forest types. The ratio showed consistent declines with age, but no difference was detected in different age groups. Additionally, the time step by which fluxes were partitioned did not affect the ratios consistently. It may indicate that higher carbon assimilation in the canopy did not translate into higher sequestration of carbon in ecosystems, but was simply a faster return time through plants to return to the atmosphere via the roots.

Barnard et al.\[54\] estimated the magnitude of response of soil N$_2$O emissions, nitrifying enzyme activity (NEA), and denitrifying enzyme activity (DEA) to elevated CO$_2$. They found no significant overall effect of elevated CO$_2$ on N$_2$O fluxes but a significant decrease of DEA and NEA under elevated CO$_2$. Gross nitrification was not altered by elevated CO$_2$, but net nitrification did increase.

Changes in plant tissue chemistry may have important and long-term ecosystem consequences. Impacts of elevated CO$_2$ on the chemistry of leaf litter and decomposition of plant tissues were also summarized using meta-analysis\[55\]. The results suggested that the nitrogen concentration in leaf litter was 7.1% lower under elevated CO$_2$ compared with that at ambient CO$_2$. They also concluded that any changes in decomposition rates resulting from exposure of plants to elevated CO$_2$ were small when compared with other potential impacts of elevated CO$_2$ on carbon and nitrogen cycling. Knorr et al.\[56\] conducted a meta-analysis to examine the effects of nitrogen enrichment on litter decomposition and found no significant effects across all studies. However, fertilizer rate, site-specific nitrogen deposition level and litter mass have influenced the litter decay response to nitrogen addition.

Meta-analysis was also used for investigating the responses of mycorrhizal richness\[57\], ectomycorrhizal and arbuscular mycorrhizal fungi, and ectomycorrhizal and arbuscular mycorrhizal plants\[58\] to elevated CO$_2$.

### 2.2 Response of ecosystem to global warming

The potential effects of global warming on environment and human life are numerous and variable. Increasing temperature is expected to have a noticeable impact on terrestrial ecosystems. Data collected from 13 different International Tundra Experiment (ITEX) sites\[59\] were used to analyze responses of plant phenology, growth and reproduction to experimental warming using meta-analysis. This analysis suggests that the primary forces driving the response of ecosystems to soil warming do vary across climatic zones, functional groups and through time. For example, herbaceous plants had stronger and more consistent vegetative and reproductive response than woody plants. Recently, similar work was done by Walker et al.\[60\] who used meta-analysis to test plant community response to standardized warming experiments at 11 locations across the tundra biome involved in ITEX after two growing seasons. They revealed that height and cover of deciduous shrubs and graminoids have increased, but, cover of mosses and lichens has decreased, and species diversity and evenness have decreased under the warming. Graminoids and shrubs showed larger changes over 6 years. This was somewhat different from previous study\[59\] in which graminoids and shrubs had the largest initial growth over 4 years. This again demonstrates that longer-term ex-
periments are essential for investigating plant response to global warming. Parmesan et al.\(^\text{[1]}\) reported a meta-analysis on species range-boundary changes and phenological shifts to global warming, which showed significant range shifts averaging 6.1 km per decade towards the poles and significant mean advancement of spring events by 2.3 days per decade. Similar results were found in another study on the effects of global warming on plant and animals\(^\text{[61]}\). More than 80 percent of species showed changes associated with temperature. Species at higher latitudes responded more strongly to the more intense change in temperature. A statistically significant change towards earlier timing of spring events has also been detected.

The sensitivity of soil carbon to temperature plays an important role in the global carbon cycle and is particularly important for giving the potential feedback to climate change\(^\text{[62]}\). However, the sensitivity of soil carbon to warming is a major uncertainty in projections of CO\(_2\) concentration and climate\(^\text{[56]}\). Recently, the sensitivity of soil respiration and soil organic matter decomposition has received great attention\(^\text{[56,62–68]}\). Several experiments showed that soil organic carbon decomposition increased with higher temperatures\(^\text{[65,68]}\), but additional studies gave contrary results\(^\text{[64–66]}\). Although results from individual studies showed great variation in response to warming, results from the meta-analysis showed that 2—9 years of experimental warming at 0.3—6.0°C significantly increased soil respiration rates by 20% and net nitrogen mineralization rates by 46%\(^\text{[2]}\).

The magnitude of the response of soil respiration and nitrogen mineralization rates to experimental warming was not significantly related to geographic, climatic, or environmental variables. There was a trend toward decreasing response to soil temperature as the study duration increased. This study implies the need to understand the relative importance of specific factors (such as temperature, moisture, site quality, vegetation type, successional status and land-use history) at different spatial and temporal scales. Barnard et al.\(^\text{[54]}\) showed that the effects of elevated temperature on DEA, NEA, and net nitrification were not significant. Based on the meta-analysis results of plant response to climate change experiments in the Arctic\(^\text{[69]}\), elevated temperature significantly increased reproductive and physiological measures, possibly giving positive feedbacks to plant biomass. The driving force of future change in arctic vegetation was likely to increase nutrient availability, arising for example from temperature-induced increases in mineralization.

Arctic plant species differ widely in their responses to environmental manipulations. Shrub and herb showed strongest response to the increase of temperature. The study advocated a new approach to classify plant functional types according to species responses to environmental manipulations for generalization of responses and predictions of effects. Raich et al.\(^\text{[70]}\) applied meta-analyses to evaluate the effects of temperature on carbon fluxes and storages in mature moist tropical evergreen forest ecosystems. They found that litter production, tree growth and belowground carbon allocation all increased significantly with the increasing site mean annual temperature; but temperature had no noticeable effect on the turnover rate of aboveground forest biomass. Soil organic matter accumulation decreased with the increasing site mean annual temperature, which indicated that decomposition rates of soil organic matter increased with mean annual temperature faster than rates of NPP. These results imply that in a warmer climate, conservation of forest biomass will be critical to the maintenance of carbon stocks in moist tropical forests.

Blenckner et al.\(^\text{[71]}\) tested the impact of the North Atlantic Oscillation (NAO) on the timing of life history events, biomass of organisms and different trophic levels. They found that the response of life history events to the NAO was similar and strongly affected by NAO in all environments including freshwater, marine, and terrestrial ecosystems. The early timing of life history events was detected owing to warming winter, but less pronounced at high altitudes. The magnitude of response of biomass was significantly associated with NAO, with negative and positive correlations for terrestrial and aquatic ecosystems, respectively.

Few case studies using meta-analysis have explored the combined effects of elevated CO\(_2\) concentrations and temperature on ecosystem. One possible reason may be due to the lack of individual studies examining both factors simultaneously. Zvereva et al.\(^\text{[72]}\) performed meta-analysis to evaluate the consequences of simultaneous elevation of CO\(_2\) and temperature for plant-herbivore interactions. Their results showed that nitrogen concentration and C/N ratio in plants decreased under simultaneous increase of CO\(_2\) and temperature, whereas elevated temperature had no significant effect on them. Insect herbivore performance was adversely affected by elevated temperature, favored by elevated CO\(_2\), and not
modified by simultaneous increase of CO\textsubscript{2} and temperature. Their analysis distinguished three types of relationships between CO\textsubscript{2} and elevated temperature: (i) the responses to elevated CO\textsubscript{2} are mitigated by elevated temperature (nitrogen, C/N, leaf toughness), (ii) the responses to elevated CO\textsubscript{2} do not depend on temperature (sugars and starch, terpenes in needles of gymnosperms, insect performance) and (iii) these effects emerge only under simultaneous increase of CO\textsubscript{2} and temperature (nitrogen in gymnosperms, and phenolics and terpenes in woody tissues). The predicted negative effects of elevated CO\textsubscript{2} on herbivores are likely to be mitigated by temperature increase. Therefore, the conclusion is that elevated CO\textsubscript{2} studies cannot be directly extrapolated to a more realistic climate change scenario.

2.3 Response of ecosystem to O\textsubscript{3}
Mean surface ozone concentration is predicted to increase by 23% by 2050\cite{74}. The increase may result in substantial losses of production and reproductive output. Individual studies on the response of vegetation to ozone varied widely because ozone effects are influenced by exposure dynamics, nutrient and moisture conditions, and the species and cultivars. In the meta-analysis on the response of soybean to elevated ozone\cite{75}, from chamber experiments, the average shoot biomass was decreased by about 34% and seed yield was about 24% lower than that without ozone at maturity. The photosynthetic rates of the topmost leaves were decreased by 20%. Searles et al.\cite{76} provided the first quantitative estimates of UV-B effects in field-based studies on vascular plants using meta-analysis. They detected that several morphological parameters such as plant height and leaf mass per area showed little or no response to enhanced UV-B, and leaf photosynthetic processes and the concentration of photosynthetic pigments were also not affected. But shoot biomass and leaf area presented modest decreases under UV-B enhancement.

2.4 The effects of land use change and land management on climate change
Land use change and land management are believed to have an impact on the source and sink of CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O. Guo et al.\cite{77} examined the influence of land use changes on soil carbon stocks based on 74 publications using the meta-analysis. Their analysis indicated that soil carbon stocks declined by 10% after land use changed from pasture to plantation, e.g. 13% decrease for converting native forest to plantation, 42% for converting native forest to crop, and 59% for converting pasture to crop. Soil carbon stocks can increase by 8% after land use changed from native forest to pasture, 19% from crop to pasture, 18% from crop to plantation, and 53% from crop to secondary forest, respectively. Ogle et al.\cite{78} quantified the impact of changes of agricultural land use on soil organic carbon storage under moist and dry climatic conditions in temperate and tropical regions using meta-analysis and found that management impacts were sensitive to climate in the following order from largest to smallest in terms of changes in soil organic carbon: tropical moist > tropical dry > temperate moist > temperate dry. Their results indicated that agricultural management impacts on soil organic carbon storage varied depending on climatic conditions influencing the plant and soil processes driving soil organic matter dynamics. Zinn et al.\cite{79} studied the magnitude and trend of effects of agriculture land use on soil organic carbon and showed that intensive agriculture systems caused significant soil organic carbon loss of 10.3% at the 0–20 cm depth, while non-intensive agriculture systems had no significant effect on soil organic carbon stocks at the 0–20 and 0–40 cm depths, however, in coarse-textured soils, non-intensive agriculture systems caused significant soil organic carbon losses of about 20% at 0–20 and 0–40 cm depths.

It is important to understand the effects of forest management on soil carbon and nitrogen because of their roles in determining soil fertility and a source or sink of carbon at a global scale. Johnson et al.\cite{80} reviewed various studies and conducted a meta-analysis on forest management effects on soil carbon and nitrogen. They found that forest harvesting generally had little or no effect on soil carbon and nitrogen. However, there were significant effects of harvest types and species on them. For example, sawlog harvesting can increase by about 18% of soil carbon and nitrogen, while whole tree harvesting may cause 6% decrease of soil carbon and nitrogen. Both fertilization and nitrogen-fixing vegetation have caused noticeable overall increases in soil carbon and nitrogen. Meta-regression was used to examine the costs and carbon accumulation for switching from conventional tillage to no-till, and the costs of creating carbon offset by forestry\cite{81,82}. The results showed that the viability of agricultural carbon sinks varied with different regions and crops. The in-
crease of soil carbon resulting from no-till system may change with the types of crops, region, measured soil depth and the length of time at which no-till was practised. Another meta-analysis on the driver of deforestation in tropical forests demonstrated that deforestation was a complex and multiform process and better understanding of these complex interactions would be a prerequisite to perform realistic projections of land-cover changes based on simulation models.

2.5 Effects of disturbances on biogeochemistry

Wan et al. examined the effects of fire on nitrogen pool and dynamics in terrestrial ecosystems. They found that fire significantly decreased fuel N amount by 58%, increased soil NH₄⁺ by 94% and NO₃⁻ by 152%, but had no significant influences on fuel N concentration, soil N amount and concentration. The results suggested that different ecosystems had different mechanisms and abilities to replenish nitrogen after fire, and fire management regimes (including frequency, interval, and season) should be determined according to the ability of different ecosystems to replenish nitrogen. Fire had no significant effects on soil carbon or nitrogen, but duration after fire had a significant effect, with an increase in both soil carbon and N after 10 years. However, there were significant differences among treatments, with the counterintuitive result of lower soil carbon following prescribed fire and higher soil carbon following wildfire.

3 Discussion

Meta-analysis has been widely applied in global climate change research and proved a valuable tool in this field. Particularly, the response of terrestrial ecosystem to elevated CO₂, global warming and human activities received considerable interests because of its importance in global climate change and numerous existing individual and ongoing studies. In general, meta-analysis can statistically draw more general and quantitative conclusions on some controversial issues compared with single studies, identify the difference and its reasons, and provide some new insights and research directions.

3.1 Some issues

(i) Some basic issues on meta-analysis still exist, including publication bias, the choice of effect size measures, the difficulty of data loss when selecting literatures, quality assessment on literatures and non-independence among individual studies. There are a lot of discussions on publication bias because it can directly affect the conclusions of meta-analysis. Recently, a monograph was published, relating the types of publication bias, possible mechanisms, existing empirical proofs, statistical methods to describe it and how to avoid it. Methods detecting and correcting publication bias included proportion of significant studies, funnel graphs and some statistical methods (fail-safe number, weighted distribution theory, truncated sampling and rank correlation test, etc.). We found that the natural logarithm of response ratio was the most frequently used measure in global change research. The advantage is that it can linearize the response ratio, being less sensitive to changes in a small control group, and provide a more normal sampling distribution for small samples. In addition, the conclusions derived from meta-analysis depend on the quantity and quality of single studies. Many studies do not adequately report sample size and variance, which made weighted effect analysis difficult. Therefore, publication quality needs to be assessed through making strict literature selection and selecting quality evaluation indicators. However, publication bias and data loss are also shared with traditional narrative reviews. It is necessary for authors to report their experiments in more detail to improve publication quality and for editors to publish all high-qualified studies without considering the results. All these could improve the quality of meta-analysis in the future.

(ii) There are also risks of misusing meta-analysis, so we must be very cautious to analyze the results. Körner expressed doubt in the meta-analysis on CO₂ effects on plant reproduction, in which a surprising conclusion was that the interacting environmental stress factors are not important drivers of CO₂ effects on plant reproduction. Körner thought that the meta-analysis provided rather limited insight because the data were not stratified by fertility of growing conditions and the resource status of test plants was not known. The authors advised that meta-analysis on aspects of CO₂ impact research must account for the resource status of test plants, and that plant age is a key criterion for grouping. They also emphasized the shift in data treatment from technology-oriented or taxonomy-oriented criteria to that control sink activity of plants, i.e. nutrition, moisture, and developmental stage. In a re-analysis of meta-analysis on the stress-gradient hypothesis, it is revealed that many studies used by Maestre et al. were not conducted along stress gradients and the num-
ber of studies was not enough to differ the points on gradients among studies. Therefore, the re-analysis did not support their original conclusions under more rigorous data selection criteria and changing gradient lengths between studies and covariance.

(iii) Some advanced methods for meta-analysis have not been applied in global climate change research. Gates\[^88\] pointed out that many methods used for reducing bias and enhancing the accuracy, reliability and usefulness of reviews in medical science have not yet been widely used by ecologists. In global climate change research, cumulative meta-analysis, meta-regression and sensitivity analyses, for example, have not been applied and reported. Cumulative meta-analysis is a series of meta-analyses in which studies are added to the analysis based on a predetermined order to detect the temporal trends of effect size changes and test possible publication bias\[^89\]. It is useful to update summary results from meta-analysis. The temporal changes of the magnitude of effect sizes were found to be a general phenomenon in ecology\[^90\]. Meta-regression can quantitatively reflect the effects of data, methods and related continuous variables on effect sizes and be used for prediction. Sensitive analysis was proposed to examine the robustness of conclusions from meta-analysis because of the subjective factors. It tests the changes of the conclusions after changing data treatments or models, for example, re-analysis after removing low-quality studies, stratified meta-analysis according to sample sizes and re-analysis after changing selected and removed literature criteria\[^91\]. These methods still have potential to be used in global climate change research.

(iv) It is necessary to update the results of meta-analysis for a given topic at regular intervals. The accumulation of science evidence is a dynamic process, which cannot be satisfactorily described by the mean effect size from meta-analysis alone at a single time point. Meta-analyses of studies on the same topic performed at different time points may lead to different conclusions. Therefore, it is important to update the results of meta-analysis for a given topic at regular intervals by including newly published studies.

(v) More emphases should be put on the effects of multi-factor interactions and long-term experiments in global climate change research. The impact of climate change is related to various fields including population genetics, ecophysiology, bioclimatology, plant geography, palaeobiology, modeling, sociology, economics, etc. Meta-analysis has not been adopted in some fields or topics such as the impact of climate change on forest insect and disease occurrence, modeling the response of ecosystem productivity to climate change, and the impact of climate change on some ecosystem as a whole. In addition, few studies were conducted on multi-factor interaction although the interaction exists in climate change in the real world\[^111\]. For example, soil respiration is regulated by multiple factors, including temperature, moisture, soil pH, soil depth and plant growth condition. Those factors and their interaction have complicated effects on soil respiration. In FACE experiments, although elevated CO\(_2\) alone increased NPP, the interactive effects of elevated CO\(_2\) with temperature, N, and precipitation on NPP were less than those of ambient CO\(_2\) with those factors\[^92\]. These results clearly indicated the need for multi-factor experiments. The impact of climate change over time is also an important issue. Particularly, most experiments on trees have been conducted for a very short term. The longest FACE experiment for forest has been established only for 10 years up to now (http://c-h2oeology.env.duke.edu/site/face.html). Long-term experiments are still needed.

### 3.2 Potential application of meta-analysis in climate change research in China

Changes of global pattern are much more important than single case study in global climate change research. Therefore, meta-analysis has great potential to be used in this field. Although meta-analysis has some limitations and risks, it has been proved to be a valuable statistical technique synthesizing multiple studies. It provides a tool to view the larger trends, thus can answer the question on larger temporal and spatial scales that single experiment cannot do. China, with its diverse vegetation and land uses, has complicated climate regions across tropical, sub-tropical, warm temperate, temperate and cold zones from south to north and plays an important role in global climate change. In addition, China has the potential to affect climate change because of its gas emission development after Tokyo Protocol came into effect. It faces a great pressure and challenge and needs scientifically sound decisions on climate change issue. Scientists have made progress and conducted many experiments and accumulated large amount of original data and results. For example, Chinese Terrestrial Ecosystem Flux Observational Research Network (ChinaFLUX) consists of 8 micrometeorological
method-based observation sites and 17 chamber method-based observation sites (http://www.chinaflux.org). It measures the output of CO₂, CH₄ and N₂O for 10 main terrestrial ecosystems in China. Chinese Ecosystem Research Network (CERN) is composed of 36 field research stations for various ecosystems, including agriculture, forestry, grassland, desert and water body (http://www.cern.ac.cn). It is necessary and important to synthesize these large amounts of data and results in order to answer some overall scientific questions at larger scale, so that the results from meta-analysis could provide scientific information and evidence for governmental decisions on climate change. It is believed that the future of meta-analysis is promising with wide application in global climate change research.

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1 IPCC. Climate change 2001-synthesis report: third assessment report of the Intergovernmental Panel on Climate Change. 2001
7 Glass G V. Primary, secondary, and meta-analysis of research. Educ Res, 1976, 5: 3—8
31 Norby R J, Luo Y Q. Evaluating ecosystem responses to rising atmospheric CO₂ and global warming in a multi-factor world. New


69 Dormann C F, Woodin S J. Climate changes in the Arctic: using plant