How have carbon stocks in central and southern Africa's miombo woodlands changed over the last 50 years? A systematic map of the evidence

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Abstract

Background: Miombo woodlands cover $\approx$ 2.7 million km^2 of central and southern Africa between dry (650 mm mean annual rainfall) and moist miombo (1400 mm) and are currently threatened by land use and land cover changes that have intensified over the last 50 years. Despite the miombo's global significance for carbon (C) storage and sequestration, there has been no regional synthesis that maps carbon stocks and changes in the woodlands. This information is crucial to inform further research for the development of appropriate policies and management strategies to maintain and increase C stocks and sequestration capacity, for conservation and sustainable management. We assembled a systematic map to determine what evidence exists for (1) changes in carbon stocks in miombo woodlands over the period 1960–2015; (2) differences in carbon density in miombo with different conservation status; (3) trends in carbon stock recovery following human disturbance; and (4) fire management impacts on carbon stocks and dynamics.

Methods: We screened 11,565 records from bibliographic databases and grey literature sources following an a priori research protocol. For inclusion, each study had to demonstrate the presence of miombo-typical species (*Brachystegia*, *Julbernardia* and *Isoberlinia*) and data on above- or below-ground carbon stocks or plant biomass.

Results: A total of 54 articles met the inclusion criteria: 48 quantitative and eight qualitative (two of which included quantitative and qualitative) studies. The majority of studies included in the final analyses are largely quantitative in nature and trace temporal changes in biomass and carbon in the miombo woodlands. Studies reported a wide range (1.3–95.7 Mg ha^{-1}) of above-ground carbon in old-growth miombo woodland. Variation between years and rainfall zones and across conservation area types was large.

Conclusions: An insufficient number of robust studies that met our inclusion criteria from across the miombo region did not allow us to accurately pool carbon stocks and trends in miombo old growth. Thus, we could not address the four questions originally posed in our protocol. We suggest that future studies in miombo woodlands take longer term observational approaches with more systematic, permanent sampling designs, and we identify questions that would further warrant systematic reviews, related to differences in C level recovery after disturbance in fallow and post-clearing re-growth, and the role of controlled fire management.

Keywords: Biomass, Brachystegia, Carbon stocks, Conservation area status, Fire management, Isoberlinia, Julbernardia, Old-growth, Re-growth, Soil organic matter

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Background

Global atmospheric concentration of carbon dioxide (CO_2) is on the rise. Changes in land use have contributed about 136 (± 55) Gt C or about 25% of total anthropogenic emissions of CO_2 to the atmosphere over the past 145 years [1, 2]. The importance of CO_2 to climate change has sparked much research on the global carbon cycle, with particular attention on carbon stocks in the main terrestrial compartments of ecosystems, mainly soils and plant biomass [3–5].

Miombo is seasonally dry deciduous woodland dominated by trees of the genera *Brachystegia, Julbernardia* and *Isoberlinia* and is the largest vegetation formation in central, eastern and southern Africa. This woodland type covers an estimated 2.7 million km^2 across seven countries (Angola, Democratic Republic of Congo (DRC), Malawi, Mozambique, Tanzania, Zambia and Zimbabwe) and consists of both dry (650 mm mean annual rainfall) and moist miombo (1400 mm mean annual rainfall) woodlands [6, 7]. The region, also sometimes referred to as the miombo ecoregion [8], has a unimodal rainfall pattern with distinct and prolonged dry seasons that last from April to October/November and an edaphic environment of typically leached, shallow and impoverished soils [9]. It is the combination of these environmental factors, together with fire, that defines the limits of the miombo ecoregion from adjacent vegetation types.

Although the miombo region has been researched from the 1960s (see [10–17] among others), miombo woodlands are poorly documented and understood compared with other world biomes [18] and have only been recently recognised as a key ecosystem, for both their biodiversity values and ecosystem services (see [9, 19, 20]). The region is important for the production of valuable hardwood timber and supports the economic livelihood of millions of people [7, 15, 21, 22]. Miombo woodland is a socio-ecological system that has been maintained by humans through a long history of harvesting, cultivation and frequent dry season fires over more than 55,000 years [17, 23–25]. However, there are indications that the last 50 years have witnessed an intensification of these land use activities driven by increasing human and livestock populations, as well as the human-induced concentration of wildlife herbivores into small conservation areas [26–29]. In addition, colonial land tenure policies coupled with a post-colonial export-oriented focus have disenfranchised local communities and left them dependent on subsistence agriculture and the exploitation of forest resources [30–33].

Lately, a number of national and regional land-use policies have done little to change this negative history. Regional policy frameworks such as the Southern African Development Community (SADC) Protocol on Forestry [34], SADC Forestry Strategy (2010) [35], and Common Market for Eastern and Southern Africa (COMESA) programme, provided policy models on forestry and climate change that member countries could adopt and further develop [36]. These regional initiatives drew from Rio Earth Summit (United Nations Conference on Environment and Development (UNCED), Rio de Janeiro, June 1992) whose declaration focused on the need for nation states to create policy environments conducive to rural livelihoods. As a result, since the 1990s miombo states have pushed participatory land use programs in many woodland areas. Although these policy initiatives aimed to conserve natural resource and woodland use, many have remained largely ineffective [37]. This is for two reasons: first, because many community programmes remain underfunded and centrally driven; and second, because these initiatives have not comprehensively addressed issues pertaining to woodland access and ownership at the local level, which indirectly encourages more agricultural expansion in miombo [37, 38]. The private sector has also played a role in exploiting miombo areas through massive investments in agriculture. This has opened up more lands for crops such as tobacco, and in some instances, triggered land grabs from local woodland users [37, 39]. The combined effects from state and private land use policies have thus adversely affected miombo woodland stocks [38, 40–43].

Because seasonally dry tropical woodlands cover 40% of the tropical forest area and contain considerable carbon stocks [44, 45], deforestation and degradation of this biome has global significance [46]. The carbon stored in the above-ground living biomass of trees is a large pool directly impacted by deforestation and forest degradation [4, 47], while soil carbon represents another important carbon sink. Most soil carbon is derived from roots rather than shoots and leaf litter [48]. Plant root systems are therefore a major carbon sink and influence processes such as soil erosion and carbon cycling [49, 50]. Like many other seasonally dry forest and woodland species, miombo trees have extensive root systems that facilitate regeneration after harvesting [51, 52]. The availability of stump coppices, root suckers and suppressed saplings in the herb layer at the time of clearing enables these woodlands to recover rapidly, depending on fire and the intensity of subsequent land use (e.g. cultivation). Many studies have shown that miombo woodlands can recover rapidly from natural and anthropogenic disturbances [7, 12, 51–60].

Miombo woodlands now comprise a variety of land covers that range from woodlands composed of tall, almost closed-canopy stands, to areas with little tree cover due to clearing for cultivation, charcoal production [59], or mining and infrastructure development [22,

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61]. Although the original extent of the woodlands is unknown, we do know that climate change has affected the spatial extent of miombo areas for some time [62–64]. For example, pollen studies show a more southerly presence of the *Brachystegia* pollen in 1–4 kyr BP sediments from near Naboomspruit and Pretoria in South Africa— areas that are well beyond the present southern limit of the genus [65]. Multiple land pressures on miombo continue today as many areas across southern Africa have rising populations and greater demands for arable land. These variations in land cover and human interference influence how much biomass and carbon the woodlands can hold, and indicate a clear need to study these shifting land dynamics. In spite of the global significance miombo woodlands may have for carbon storage and sequestration, current knowledge of their contribution to global pools is limited [66], and there has been no regional synthesis of carbon stocks and changes in miombo systems to inform policy and management strategies. This map seeks to address this gap by assembling an evidence base of research, and highlighting evidence gaps, which can contribute to agenda-setting for areas of further research which seek to understand the changing land dynamics in miombo woodlands.

Objective of the review

An a priori systematic review protocol [67] describes our objectives and methods in detail. A summary is presented here, and highlights amendments that we made when developing the systematic map.

The original objective of the systematic review, detailed in the protocol, was to assess the impact of land use and land cover change on carbon stocks in miombo woodlands since the 1950s [67]. However, after assessing the available data, we found many historical studies lacked measurements of carbon or biomass, and often that studies did not clearly describe the associated land use cover change, practice, or related land use policies. As such, it became necessary and important to survey the quantity and quality of evidence on land use practices and land use policy in the miombo with a systematic mapping approach. Consequently, we reformulated the review's original questions to link land use practice and policy to land cover change and carbon stocks in miombo areas over the last 50 years. We used the following questions to guide our mapping of studies:

(1) What evidence exists for changes in carbon stocks in miombo woodlands over the period 1960–2015?
(2) What evidence exists for differences in carbon density in miombo with different conservation status?
(3) What evidence exists of trends in carbon stock recovery following human disturbance?
(4) What evidence exists of fire management impacts on carbon stocks and dynamics?

To answer these questions we classified miombo areas by their legally designated protection status based on the conservation categories of the International Union for Conservation of Nature (IUCN).[1] These include: national parks (NP), forest reserves (FR), game management areas (GMAs) and open areas (OA). In miombo countries, many protected forestry and wildlife areas fall under NPs and FRs, with GMAs also supporting NPs [68]. Forest reserves are split into national and local FRs, and include botanical gardens and sanctuaries. National wildlife and public forestry institutions jointly manage local FRs and GMAs in conjunction with local leadership councils (e.g. chiefs). Under the IUCN conservation categories, OAs have no conventional protection status; GMAs fall in the IUCN conservation area category VI (resource reserve) in which only classified fauna is protected; GMAs and FRs (local and national) fall in the IUCN conservation area category VIII (multiple use management area or managed resource area) which, depending on the establishment objective, may be protected from human activities such as settlements or where harvesting is legally permissible; and NPs fall in the IUCN conservation area category II or IV (nature conservation reserve or managed nature reserve or wildlife sanctuary) in which legal protection bars anthropogenic ecosystem disturbances [69].

While these IUCN categories have been followed in miombo countries, they often act as functional designations for national government forestry policies and vary in how well their protection status is upheld. Wildlife parks, for example, have received much more attention (in terms of restricted access as they fall under NPs) compared to FRs, which is why some authors described FRs as reservations for commercial timber rather than protected forests [70]. Lately, because of growing social and political pressures for access to land and other natural resources, NPs have also suffered from habitat loss and fragmentation, resulting in unprecedented threats to woody cover and wildlife [71]. Similarly, GMAs and local FRs have been affected by agricultural expansion and greater demands for natural resources. In Zambia, for example, these areas are contested, and over time many protected areas have been degazetted and given away to settlers [72, 73].

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[1] Many of the protected areas (e.g., forestry reserves) in miombo countries have not been widely studied. Burgess et al. [70] have observed the link between these reserves and the global reservation system (as outlined in IUCN protected area categories) is weak especially since they seem to be nationally driven rather than globally.
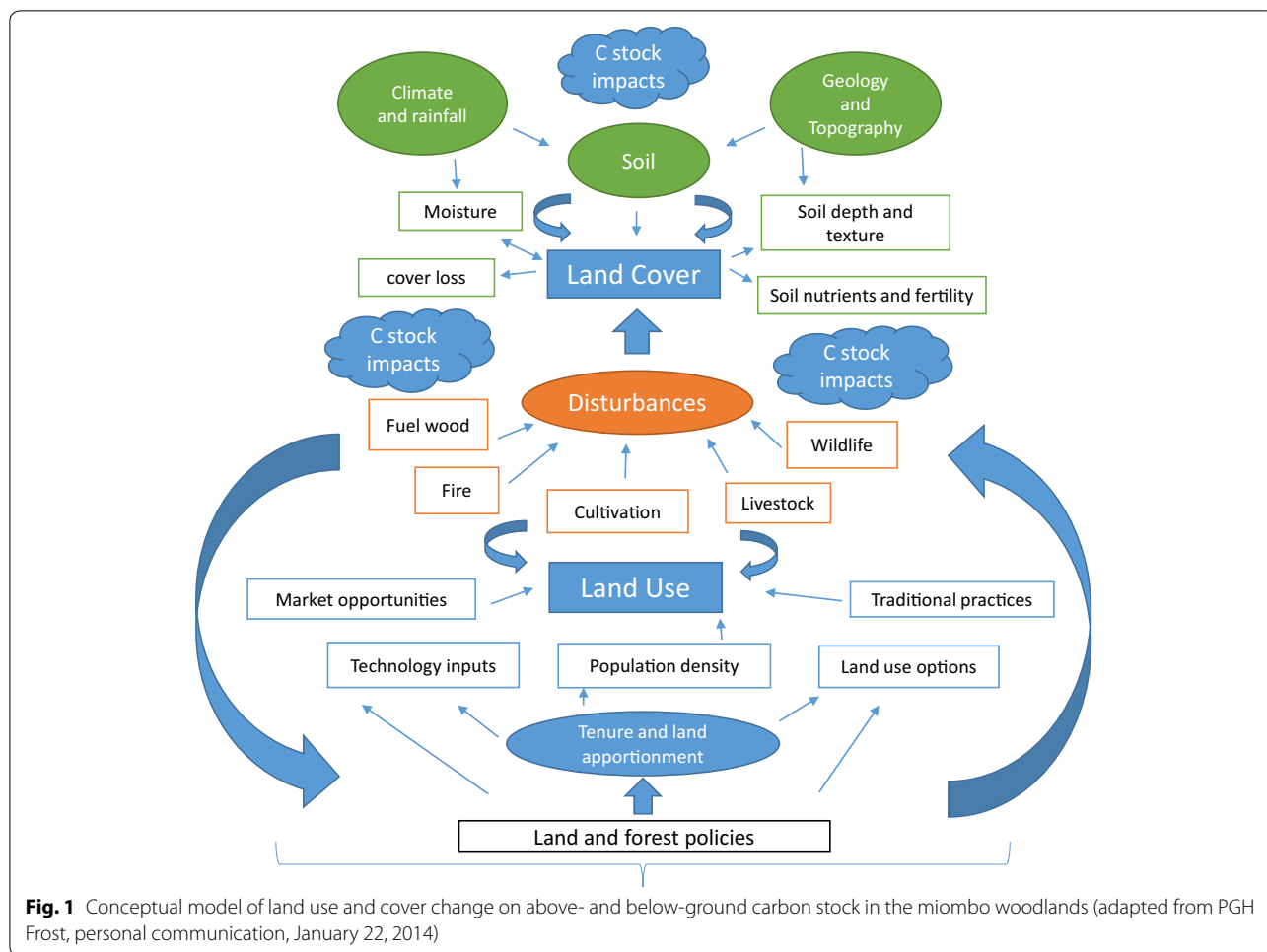
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Fig. 1 Conceptual model of land use and cover change on above- and below-ground carbon stock in the miombo woodlands (adapted from PGH Frost, personal communication, January 22, 2014)

We then assessed the best available evidence to understand the impacts of major land use activities (which include fire, herbivory, wood harvesting, woodland conversion and cultivation) on above and below-ground carbon stocks in miombo woodlands. Figure 1 shows how we originally conceptualised the drivers and impacts of land use change on above- and below-ground carbon stocks in miombo woodlands [67].

Methods

Literature searches

Our search strategy was implemented between April and November 2015. We consulted a wide range of historical, academic (peer-reviewed) and grey literature sources to locate studies that examined land use change in miombo woodlands since 1950 (Table 1; Additional file 1). The search for studies from the 1950s onwards was chosen for two main reasons: first, because we estimated this to be enough time to document land use change and impacts within the region; and second, because there was unlikely to be usable data

before 1950 for the purposes of the map. To find historical, unpublished or highly relevant field data from miombo countries, we hand-searched library resources and contacted experts in the field. To identify relevant peer-reviewed literature, we developed and tested a search string that used search terms (and synonyms) from the population, exposure and outcomes of interest (Table 2). This search string (and shorter versions) were used across nine publication databases. Where using a long search string was not feasible, such as in Google Scholar and other academic and grey literature websites, the search string was shortened and simplified. Additional file 1 shows the search strings, keywords and literature sources used during the search, and Table 1 shows the original list of literature sources. One noted change from the original research protocol is that due to time and resource constraints, fewer government offices and private companies than planned were contacted.

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Table 1 Databases and organizations searched

Publication databases

  Archive of Tropical Forestry Inventory ATROFI_UK

  Electronic Data Information Science (EDIS)

  CAB Direct

  Natural Resources Canada (NRCan) Library Catalogue

  Web of Knowledge

  Scopus

  Wiley Online

  JSTOR

  African Journals Online

Search engines

  Google Scholar

Organizational websites

  African Forest Forum

  FAO

  Global Forests Resources Assessment

  National Forest Monitoring and Assessment (NFMA) of the fAO

  The Consultative Group on Agricultural Research (including CIFOR and ICRAF)

  United Nations Environment Programme (UNEP)

  Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT): Conservation and sustainable management of below-ground biomass project

  Miombo Network list serve

  Commonwealth Scientific Industrial Research Organisation (CSIRO)

  World Bank

  Integrated Land Use Assessment Phase 1 and 2, Zambia

  National vegetation mapping project (VegRIS) Zimbabwe

  Winrock International

  KEW Royal Botanic Gardens

  Land and Timber Services (LTS) International

  Japan International Cooperation Agency (JICA) Mozambique information

  Deutsche Gesellschaftfür Internationale Zusammenarbeit GmbH (GIZ)

  Multifunctional Agriculture: harnessing Biodiversity for Sustainable Agricultural Production and Ecosystem Services (SAPES), Lund University

  Total Land Care—Malawi

  Conservation International

  World Wildlife Fund

  International Union for the Conservation of Nature

  National Forestry Resources Monitoring and Assessment, Government of Tanzania (NA FORMA)

  African Soil Information Service (Afsis)

Private Sector

  Agricultural Research and Extension Trust—Malawi

  British American Tobacco, Alliance One (Malawi, Zambia)

  Zambia Land Alliance

  NWK Agri-Services (prior name of Dunavant)

  Zambia Leaf

  Limbe Leaf—Malawi

Table 1 (continued)

Universities and Government offices

  Forest Research Institute of Malawi (FRIM)

  Oxford Department of Plant Sciences

  Zambia Government: Forest Department, Department of Environment and Natural Resources Management Department (ENRMD); Climate Change Secretariat

  Tanzania Forest Research Institute (TAFORI)

  Forestry Commission, Harare; Forest Research Center

  University of Zimbabwe, Institute of Environmental Studies, and the Centre for Applied Social Science (CASS)

  Bangor University

  University of Sokoine, Department of Agriculture, Tanzania

  University of Zambia, School of Natural Sciences and Agricultural Sciences

  University of Edinburgh, School of Geosciences

  University of Aberdeen, Forestry & Agriculture Department

  Climate Action Network International; ZERO

  Southern Alliance for Indigenous Resources (SAFIRE), Harare

  National University of Science and Tech, GIS mapping & Inventory at Forest Research Centre, Bulawayo, Zimbabwe

  Environmental Management Agency (EMA), Harare

  Zambia Environmental Management Agency (ZEMA)

  Ministry for Coordination of Environmental Action (MICOA), Mozambique

  Department of Environmental Affairs, Malawi

  Additional publications from experts

Article screening and study inclusion criteria

After the articles were compiled and duplicates removed, a review team (4–9 people) used a priori inclusion criteria to identify relevant studies (as shown in Table 3) [67]. The criteria were that studies had to be within the miombo region of sub-Saharan Africa, defined by the presence of species in the genera of *Brachystegia*, *Julbernardia* and *Isoberlinia*. Studies also had to demonstrate a land use practice that impacted above- or below-ground carbon or biomass (which included measurements of vegetation density and diameter at breast height). Qualitative studies had to demonstrate links between land use change and biomass or carbon change, including discussions of forest and land policies or tenure arrangements.

Before screening began, a Kappa analysis [74] was done to compare reviewer agreement on a random sample of 100 titles and abstracts. This was to measure inter-rater agreement in applying the inclusion criteria to studies (where all reviewers must achieve a score of > 0.6 in agreement of 100 articles). Randolph's free marginal multi-rater Kappa [75] was used to score

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Table 2 Search terms

Population	
Miombo woodland	miombo OR woodland* OR "Zambez* phytoregion" OR brachystegia OR julbernardia OR isoberlinia OR savanna* OR forest* OR "standing stock" OR biomass
Countries	
	Zambia OR Angola OR Malawi OR "Democratic Republic of Congo" OR Mozambique OR Zimbabwe OR Tanzania OR "South Africa" OR Burundi OR "Belgian Congo" OR Zaire OR Rhodesia OR Nyasaland OR Tanganyika OR Africa
Exposure	
Land use	timber OR fire OR "forest product*" OR "wood product*" OR "natural resource*" OR "land cover" OR "land use" OR "land tenure" OR "land degradation" OR swidden OR citemene OR chitimene OR "slash AND burn"+- OR fallow OR "shifting cultivation" OR grazing OR infrastruct* OR mining OR migrat* OR wildlife OR bushmeat OR fodder OR mushroom* OR fuelwood OR woodfuel OR charcoal OR refugee OR log* OR agroforestry OR disturb* OR medicin* OR "forest management" OR "land management" OR "land polic*" OR "forest polic*" OR livelihood* OR measure OR density OR livestock OR "management regime"
Outcome	
Wood OR biomass OR carbon	emission* OR vegetation OR wood* OR biomass OR carbon OR stock* OR flux* OR "above ground" OR "below ground" OR "basal area" OR sequest* OR accumulate* OR model OR estimat* OR ndvi* OR recover* OR "land use change"++ OR rootstock

agreement for 2 rounds of Kappa analysis between 9 and 8 reviewers, respectively. Both rounds had over 0.6 agreement, and reported 0.67 (9 reviewers) and 0.64 (8 reviewers) free marginal Kappa scores. During each round, disagreements in applying the inclusion criteria were discussed and these notes were saved in a screening guidance sheet that was shared with all reviewers. Once the second round of Kappa test was completed and discrepancies discussed, screening of articles began.

The review team screened articles through two main stages: title/abstract and full-text levels. During the first stage, seven reviewers screened 11,565 titles and abstracts simultaneously with the online software tool Abstrackr.[2] Abstrackr allows multiple reviewers to screen titles and abstracts independently and collates results. After the first round was completed, a smaller review team (five people) re-screened abstracts with Abstrackr. This was partly because of over-cautiousness by the larger review team in reviewing abstracts, but also because of the large number of records remaining and the limited resources of the team. The reviewers followed the same inclusion criteria but excluded articles that were highly likely to be ineligible for the map. These results were then imported into a Microsoft Excel file for full-text review.
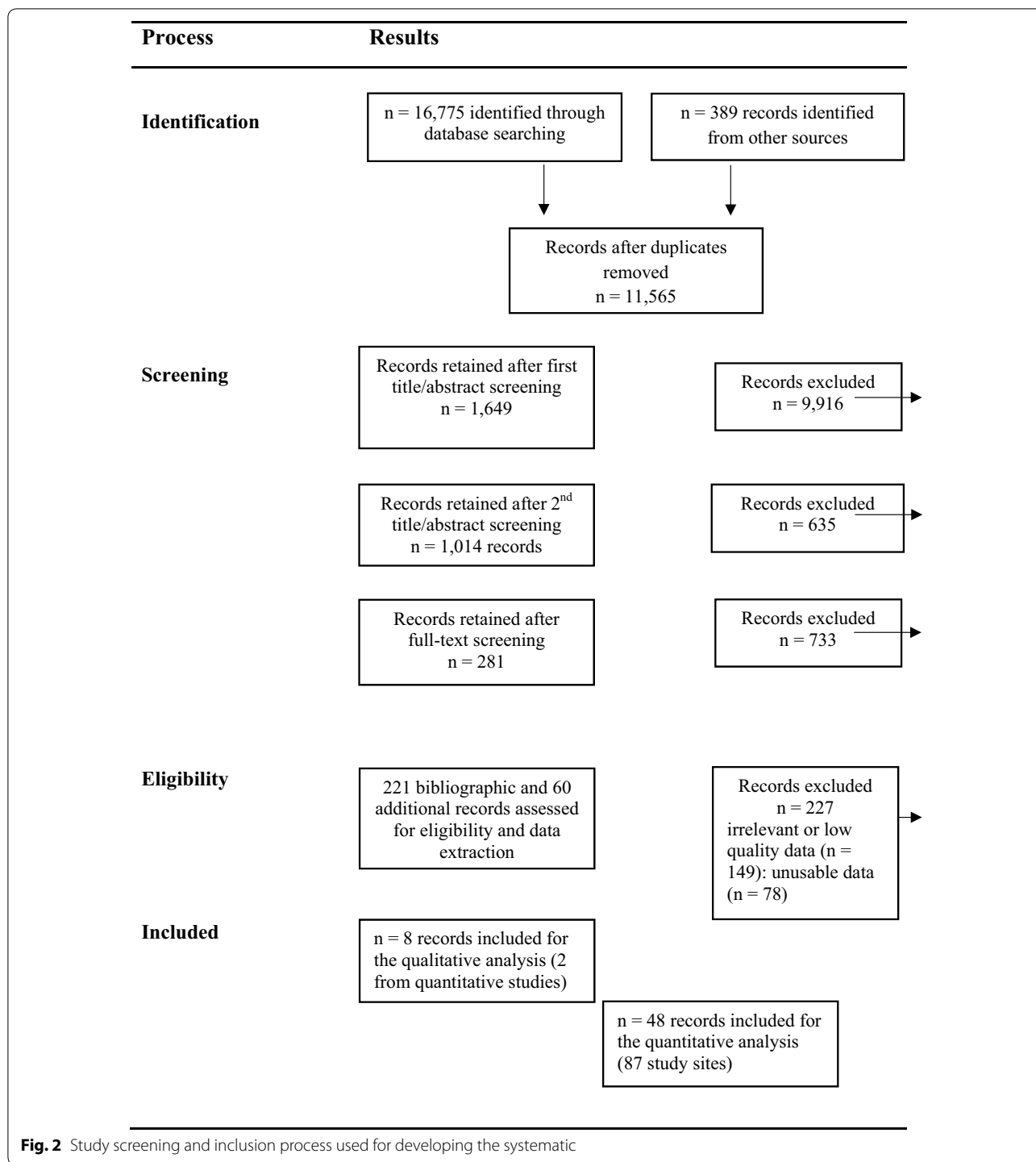
Full text screening was the second stage of screening. A small review team (four people) screened 1014 full-texts online according to the inclusion criteria. Records which passed this stage were downloaded and included

in the map for further eligibility screening in study validity assessment and data coding stages.

Study validity

Five reviewers were involved in assessing study validity and data coding processes as described in [67] and shown in Additional file 2. The study validity assessment tool, as proposed in the original protocol [67], was discussed with the Advisory Group and tested iteratively on selected papers to ensure uniformity of application. The principles outlined by Bilotta et al. [76] were used as the basis for the tool's format, namely: it has "construct validity" (the included criteria measure what they purport to be measuring), it facilitates good inter-reviewer agreement, it can be applicable across study designs, and is relatively quick and easy to use. It used 14 questions to score records on study type and the strength of presentation of data. Because of the high variability of methods used between both qualitative and quantitative studies, the tool used key variables that focused on the relevance and clarity of data presentation but, at the same time, were flexible enough for the many types of study designs encountered. These questions were answered with a yes (1), unclear (0.5), or no (0) and scored with a quantitative ranking assessment (Table 4, Additional file 2). Important contextual social information (e.g. tenure arrangements and woodland management policies linked to land use change) and study site information (for plot measurement studies) were also similarly ranked. An overall cumulative quantitative score, based on the validity of data reporting, was given to each record. This collated studies into a relative ranking system of high (13–14); medium (9–12.5); low (6–8.5); and very low study validity

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[2] Abstrackr is a simple software tool developed by Brown University to enable quick screening of study titles and abstracts. See https://www.brown.edu/academics/public-health/research/evidence-based-medicine/research-initiatives/software-0.
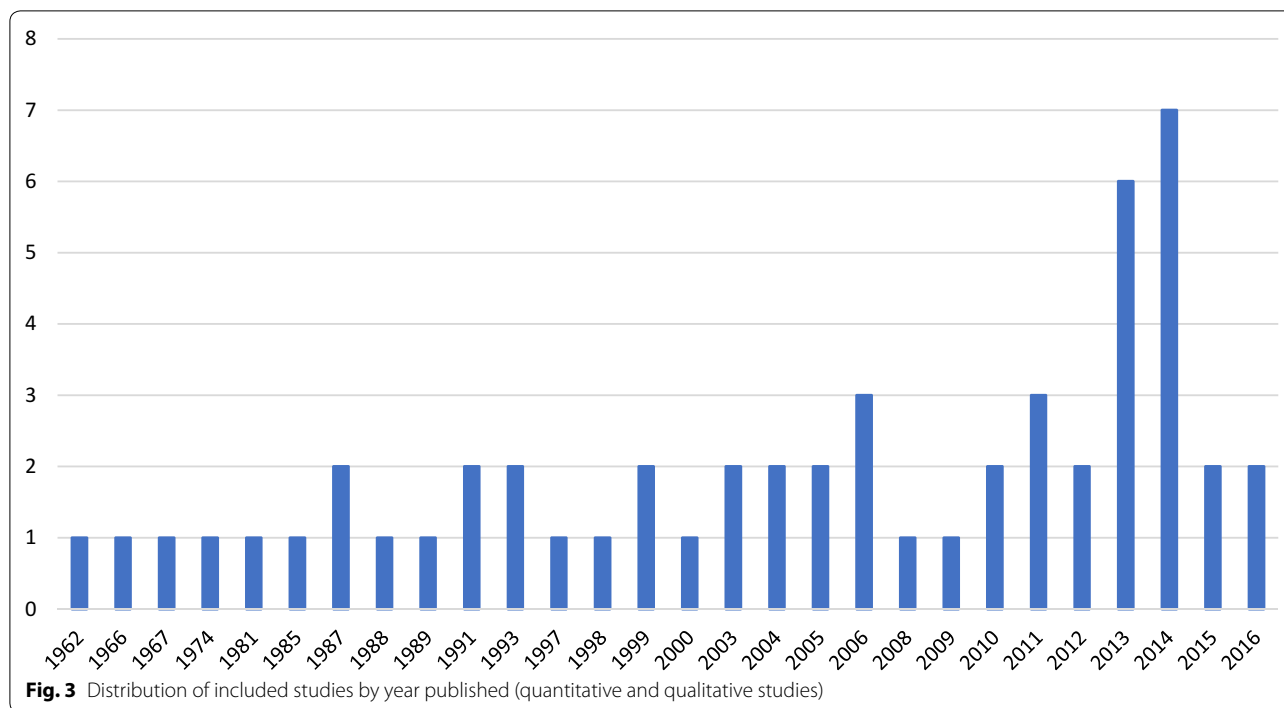
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Process	Results

Identification

n = 16,775 identified through database searching

n = 389 records identified from other sources

Records after duplicates removed
n = 11,565

Screening

Records retained after first title/abstract screening
n = 1,649

Records excluded
n = 9,916

Records retained after 2nd title/abstract screening
n = 1,014 records

Records excluded
n = 635

Records retained after full-text screening
n = 281

Records excluded
n = 733

Eligibility

221 bibliographic and 60 additional records assessed for eligibility and data extraction

Records excluded
n = 227 irrelevant or low quality data (n = 149): unusable data (n = 78)

Included

n = 8 records included for the qualitative analysis (2 from quantitative studies)

n = 48 records included for the quantitative analysis (87 study sites)

Fig. 2 Study screening and inclusion process used for developing the systematic

(0–5.5). Records which scored very low were excluded from the map.

Study coding strategy
After a study's validity was assessed, a Microsoft Excel template was used to record as many study metadata elements as were available in the articles. This information included bibliographic information, study site information, details of evidence type and methodology, study context, and outcomes, as shown below. Before data coding began, five reviewers first tested the template with several studies and then discussed

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Fig. 3 Distribution of included studies by year published (quantitative and qualitative studies)

discrepancies. This was to ensure there was the same understanding in applying and answering the data coding categories. One reviewer collated the data for review and further analysis (Additional file 3, quantitative information).

- *Bibliographic information*: author, year, title, publication type, place of publication/publisher.
- *Study site information*: location of study, exposure(s), duration of the exposure(s).
- *Details of evidence type*: source, study design, methodology, parameters used in the analysis, duration and year of study.
- *Context and relevant detail considered in the study*: conceptual link between the exposure and biomass or carbon stock.
- *Evidence of outcomes*: reported presence of data and effect on biomass and carbon, duration of impacts, scale and suitability of impacts. Note that, in a significant change to the protocol (and in keeping with all systematic maps), primary outcome data are not included; we indicate only the presence of such data in the studies, which will assist future systematic reviews that may explore related questions in more detail.

Results

Study inclusion

We screened 11,565 records by title and abstract (after removing duplicates, Fig. 2). Many records were excluded because they did not show the presence of the defined miombo tree species, or failed to directly link land use change to impacts upon plant biomass or above or belowground carbon. Title/abstract and full-text screening excluded 11,284 records, leaving 281 records (221 peerreviewed articles and 60 additional sources) that were appraised for eligibility. During this process, 227 records were excluded because of low validity (see Additional file 4 for excluded studies). What particularly limited the number of included records was poor documentation of information on the Population—failure to demonstrate that studies were in miombo areas as defined by the species outlined in the protocol—and Outcomes—poor or missing information on how land use changes impacted carbon or biomass in defined measurements. In total, 54 records were found to have usable data for the map, comprising 48 quantitative and eight qualitative records (two records are double-counted as they reported both quantitative and qualitative data).

Descriptive statistics

Of the 54 records included, three records were dissertations, three records were reports, and 48 records were journal articles, covering the years between 1962–2016 (Fig. 3). All records contained only one unique study.

Table 3 The subjects, exposures, comparators, and outcomes of relevance

Relevant subject	Relevant exposures	Relevant comparators	Relevant outcomes
Miombo woodlands: as defined by the presence of *Brachystegia, Julbernardia* and *Isoberlinia* species	Land use and land use practices on above and below-ground carbon stocks, which include: Energy use (charcoal, fuelwood) Poles (home use) Commercial timber harvesting Agriculture (shifting cultivation, expansion) Livestock (browsing of saplings) Wildlife damage (e.g. elephants) Beekeeping (making of traditional hives) Destructive harvesting of NTFPs (e.g. edible caterpillars, fruits) Protected areas Agroforestry Fire (natural; managed and wild) Rainfall; drought; temperature variability Infrastructure development (roads; mining)	Alternative land uses and practices compared either as controlled 'plots' (study areas defined in the primary studies) with different land-use strategies set up and analysed at the same time, or before-and-after intervention comparisons on the same plots	Any measured change in: Carbon stocks (including plant carbon and soil carbon) Plant biomass (including above and below ground)

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Table 4 Study validity assessment criteria

	Yes	Unclear	No
	1	0.5	0
Assessment criteria			
1. Does the study compare relevant subject, exposures, comparators and outcomes of interest?	Yes or no only. If no, exclude		
2. Is the duration of the study adequate for the outcomes obtained?			
3. Is the sample size clearly explained and adequate for the study?			
4. Are the data collection methods clearly explained and replicable?			
5. Is the qualitative or quantitative analysis clearly explained and replicable?			
6. Are the results and conclusions logical and derived from the data obtained?			
7. Are confounding factors explained?			
Contextual social information			
8. Is the historical context of the study presented?			
9. Is the ecological context of the study presented?			
10. Is the political context of the study presented?			
Site and population information			
11. Is information provided on the study site's soil?			
12. Is information provided on the study site's climate?			
13. Is seasonality taken into account?			
14. Is vegetation documented?			

Two studies were assessed as having high validity; 51 studies were assessed as medium; and one study was assessed as having low validity. These factors are discussed further below.

Qualitative studies
Eight qualitative studies directly related miombo land use practices to impacts on woody biomass and carbon. The study locations were as follows: Malawi (n = 2), Zambia (n = 2), Tanzania (n = 2), Zimbabwe (n = 1) and one global study. Most studies were journal articles (n = 7) and one study was a dissertation. Three studies used mixed methods (quantitative and qualitative approaches including interviews, and measured transects and plots), while five studies employed qualitative methods only. In the assessment of study validity, one had high study validity, and six studies were scored as medium and one low.

The majority of qualitative studies (n = 7) focused on exposures around the use of local forest resources for livelihoods. Only one study focused on agricultural practices in forest areas. One study made direct links to forest loss and carbon, and two studies attempted to measure forest resource extraction. The other studies (n = 5) used narrative evidence and description to describe land and woodland practices. All studies linked land and woodland uses (i.e. exposures) to impacts on woodland or biomass (i.e. outcomes) but

were extremely site specific and therefore difficult to generalise.

All eight studies documented how the miombo woodlands were important for local livelihoods, and thus advocated local level forest management. For example, one study argued for the use of local knowledge in woodland management [77], and almost all studies (n = 7) called for decentralisation of management to local levels. Mbwambo et al. [78] most clearly demonstrated the critical issues affecting woodland governance at different scales, by showing that local forestry reserves (e.g. State) had as much tree loss as open (e.g. communal) woodlands in Tanzania. This reflects the finding by Roe et al. [79] that all miombo countries have some form of community forestry management scheme captured in forest policies, but that the failure to deploy these policies has not been fully understood. However, in terms of broader governance aspects of miombo woodland management, the evidence base was limited. No studies discussed the implications for adopting regional forestry management models (i.e. SADC and COMESA) or global models such as REDD+, and the necessary land use or forest policy changes needed [80].

Quantitative studies
Studies were from 87 locations in Malawi, Mozambique, Tanzania, Zambia and Zimbabwe (Fig. 4). Five of these sites lie outside the main miombo woodland range as it is typically known but were included because the flora of the sites include species of *Brachystegia* and *Julbernardia*

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as defined by the inclusion criteria [67]. The sites extend over a large geographical region and differ in some biophysical conditions. Notably, no sites were located in Angola, northern Mozambique or the DRC, and more of the studies occurred in dry (n = 31) compared to moist miombo (n = 18) (one article had plots in both dry and moist miombo) (see Fig. 5).

Research design

Data in the relevant studies (Table 5) were collected using diverse sampling designs at sites with heterogeneous geographical, ecological and land use conditions. Few studies (n = 17) used permanent sampling designs; most used chronosequence study designs in old and re-growth plots (n = 494) (Fig. 6).

The majority of the data reported on above-ground biomass, basal area and soil organic matter (Table 5 and Fig. 7). In terms of woodland cover, the majority of study plots were in re-growth (n = 298) compared to old-growth (n = 213) woodland. Re-growth study sites were further classified into either fallow re-growth (n = 163) (i.e., woodland regenerating at a site/plot following abandonment of crop cultivation); or woodland re-growth (n = 135) (woodland regenerating at a site/plot following clearing, e.g. for charcoal production or tsetse fly control, without experiencing crop cultivation). In terms of conservation area status, the data were distributed as follows: 5 in GMAs, 15 in NPs, 72 in FRs and 419 in OAs (see Fig. 8).

Woodland management practices (harvesting, fire regime and herbivory) were not explicitly described for the majority of sites, which would constrain any analysis of effects of these practices on carbon stocks and sequestration (Fig. 9).

Discussion

Carbon stocks in old-growth miombo woodlands

Average above-ground carbon stock in old-growth miombo woodland across all studies was 33.9 ± 1.3 Mg C ha^{-1}, with a wide range (1.3–95.7 Mg ha^{-1}). However, variation between years (i.e. different data sets) and between rainfall zones was large, and the wide range suggests that sampling occurred randomly across the region. Given this large variation, future assessments would need to differentiate by rainfall/aridity zones, history of land use and human interventions.

A number of studies have asserted that the level of disturbance in miombo woodlands increases with decreasing distance from human settlements and road infrastructure [17, 126–128], and that miombo woodlands are losing their potential to hold C stocks, rather

Fig. 4 Distribution of miombo woodlands (shaded area based on [9]) and study sites/places (empty circles) included in the map. Some sites/places represent more than one study. An online geo-map of data is available here: https://oxlel.github.io/evidencemaps/miombo/
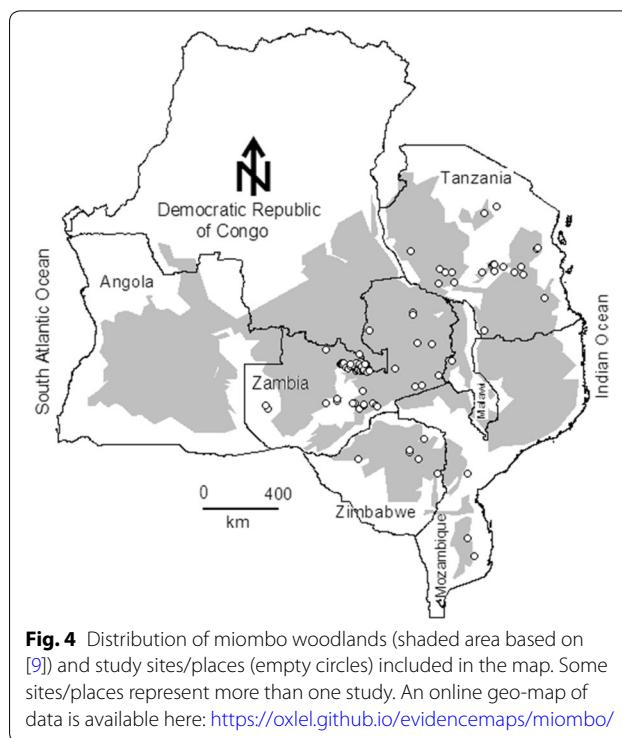
becoming net emitters of CO_2 into the atmosphere [102]. A global study found human pressure (measured through human population density, land transformation and electrical power infrastructure) on terrestrial ecosystems, including protected areas, to have increased by 64% since the 1990s [129].

However, there is scant evidence in the available literature of miombo biomass variation with distance from settlements. It is also known that biomass depends on the aridity levels [130], drainage and effective rooting depth [51], as well as rainfall [131]. Data for these factors in the studies we mapped are not available in a uniform way, and this would severely limit future meta analysis testing this hypothesis. A further limitation of studying biomass across sites and years from the a posteriori compilation of available data sets comes from the different sampling designs and spatial confounding factors between studies. Further, the studies do not represent any systematic sampling across the whole miombo region and its environmental and climatic gradients. Some countries have been completely omitted from the map because of the lack of data. Long-term observational data in the same stands under controlled intervention regimes of different intensity would be needed to address specifically the question of stand biomass degradation over time.
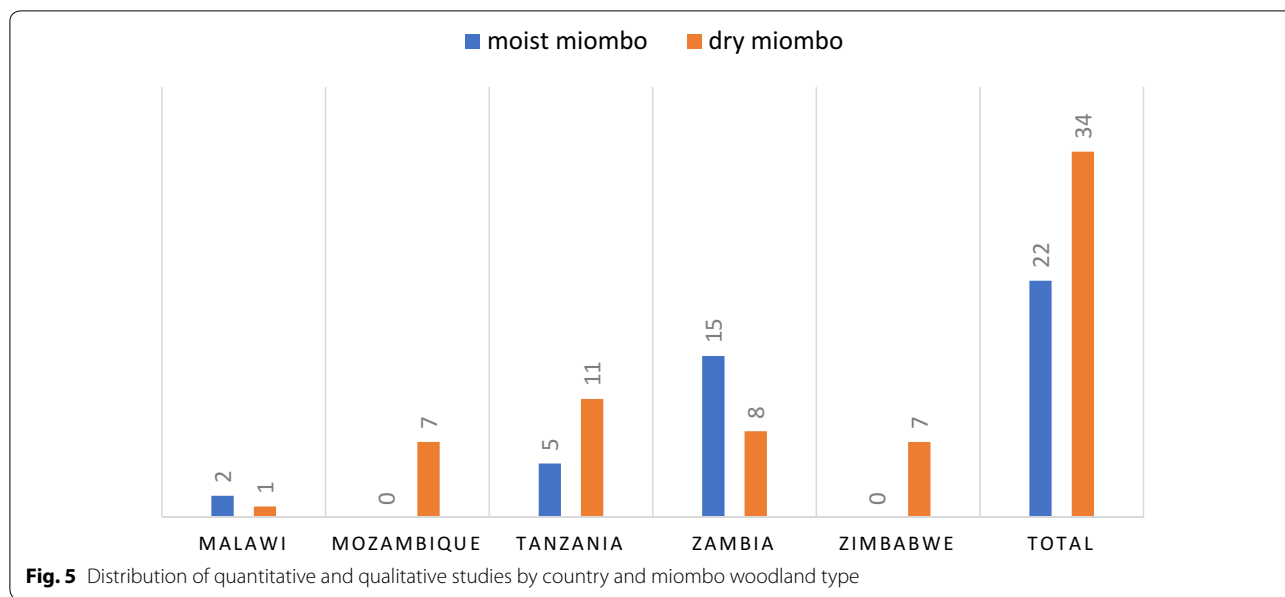
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Fig. 5 Distribution of quantitative and qualitative studies by country and miombo woodland type

Table 5 The types of methods, data outcomes and studies included in the map

Data type	Method description	No of measurements	Studies included
Basal area	m^2 ha^{-1} at 1.3 m above-ground	181	Lees [81]; Boaler and Sciwale [12]; Endean [11]; Strang [54]; Chidumayo [56, 82–85]; Kwibisa [86]; Chamshama et al. [87]; Banda et al. [88]; Williams et al. [89]; Ryan and Williams [90]; Mbwambo et al. [78]; Chomba et al. [91]; Kashindye et al. [92]; Sawe et al. [93]; Treue et al. [94]
Biomass	Mg ha^{-1}	187	Guy [95]; Stromgaard [96]; Chidumayo [97, 98]; Grundy et al. [99]; Smith [100]; Sambane [101]; Kutsch et al. [102]; Kashindye et al. [92]; Ando et al. [103]; Ryan et al. [104]; *Sawe et al.* [93]; Hofstad and Araya [105]; Jew et al. [17]
Above-ground carbon	Mg C ha^{-1}	105	*Stromgaard* [96]; *Guy* [95]; *Chidumayo* [97]; *Grundy et al.* [99]; *Smith* [100]; *Sambane* [101]; *Kutsch et al.* [102]; *Kashindye et al.* [92]; *Ando et al.* [103]; *Sawe et al.* [93]; *Hofstad and Araya* [105]; Shirima et al. [106]; *Jew et al.* [17]
Tree AGB & BGB	kg tree^{-1}	34	Ryan et al. [25]; Chidumayo [107]; Mugasha et al. [108]
Soil organic matter	% per soil volume	361	Araki [109]; *Kwibisa* [86]; Chidumayo and Kwibisa [110]; Mapanda et al. [111, 112]; Muposhi et al. [113]
Soil organic carbon	Mg C ha^{-1}	108	Jenkinson et al. [114]; *Chidumayo and Kwibisa* [110]; Walker and Desanker [115]; Anonymous [116]; *Williams et al.* [89]; Rossi et al. [117]; *Kutsch et al.* [102]; *Ryan et al.* [25]; Woollen et al. [66]; *Chidumayo* [98]; *Mapanda et al.* [112]; *Ando et al.* [103, 118]; *Muposhi et al.* [113]; Shelukindo et al. [119]; Winowiecki et al. [120]
Policy and land use change			McGregor [77]; Abbot [121]; Hogan et al. [122]; Grace et al. [123]; Culas [124]; Davies et al.[125]; *Mbwamdo et al.* [78]; *Chomba et al.* [91]

Studies in italic reflect those listed more than once

AGB & BGB, above- and below-ground biomass respectively

Below-ground carbon

Miombo woodland soils contain considerable amounts of organic matter, which forms a large below-ground pool of carbon [115]. Two soil qualities have an important bearing on soil carbon. First, total soil organic matter (SOM) in miombo soils is often concentrated in the top 30 cm of the soil, with contents ranging from 1 to 2% [89, 132, 133]. Second, soil bulk density (SBD), which ranges from 1.2 to 1.4 in miombo soils [89,
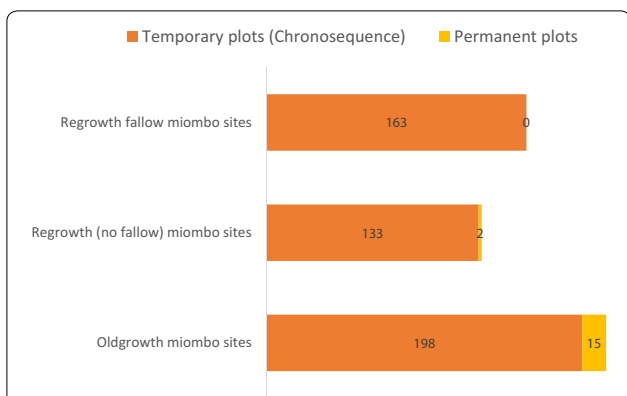
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Fig. 6 The distribution of methods used in quantitative studies, organised by plots and types of miombo cover
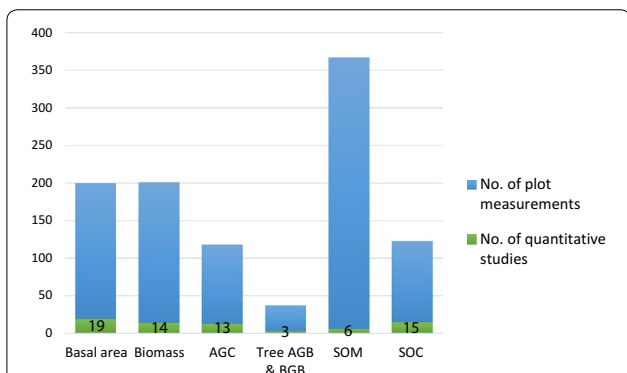

Fig. 7 The distribution of outcomes within quantitative studies by outcome and number of plot measurements
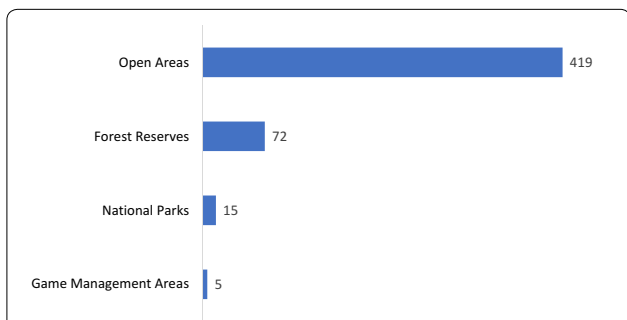

Fig. 8 Distribution of miombo study sites as classified by IUCN conservation status (quantitative studies only)

110]. Bulk density was not reported in all the studies reviewed [115].

Few studies have estimated below-ground plant biomass in the miombo. In general the root:shoot (R/S) ratio is used to estimate below-ground biomass and this ratio varies with tree size in miombo woodlands [25, 107, 108].

Since young and small trees tend to have higher below-ground to above ground biomass ratio than old and large ones, it is important to use different R/S ratios for regrowth miombo dominated by small trees and for old-growth miombo dominated by large trees. Appropriate ratios given in [107] of 0.77 and 0.54 for re-growth and old-growth miombo woodland, respectively, would need to be applied to raw data to estimate below-ground biomass and carbon effectively across studies.

Loss of miombo woodland area

Miombo woodland area losses have been observed to varying degrees of intensity at landscape level, largely driven by land clearing for agriculture and wood extraction for energy, both processes often going hand in hand [21]. Governments have been working to address tree loss in general as noted in the promulgation of new forest policies, acts and regulations in the wake of the developments after the Rio Earth Summit (UNCED, Rio de Janeiro, June 1992) [134, 135]. While regulations exist, the situation is not likely to change soon without sufficient budgetary support, enforced regulations, the participation of communities, and awareness and capacity building.

Carbon stocks along a conservation gradient

Wegmann et al. [136] found that vegetation cover change is faster outside than inside protected areas, and Geldmann et al. [129] observed that human impact on protected areas is correlated to their location and IUCN management category. Cumming et al. [137] observed that woodland degradation in protected areas in southern Africa is largely caused by elephants and fire. Studies included in the map report varying figures for C stocks along a conservation gradient in miombo woodlands; future meta analysis could test whether the data are in line with findings by Banda et al. [88] in western Tanzania. Indeed, given the increasing number of reports of human encroachments into national parks located within miombo woodlands (see [121, 126, 138]), human and elephant pressure in protected areas may have made C stocks in conservation areas just as vulnerable to loss as in unprotected areas. This would present considerable challenges to efforts to conserve C stocks in the miombo region of central and southern Africa, e.g. for initiatives to reduce greenhouse gas emissions and increase carbon sequestration that are under way in parts of the region [139–141]. These initiatives include REDD+ (Reduced Emissions from Deforestation and forest Degradation plus enhancement of forest stocks), which creates incentives for developing countries to protect, better manage and wisely use their forest resources and thereby

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Fig. 9 Distribution of included quantitative studies mentioning land use practice types (by plots/sites)
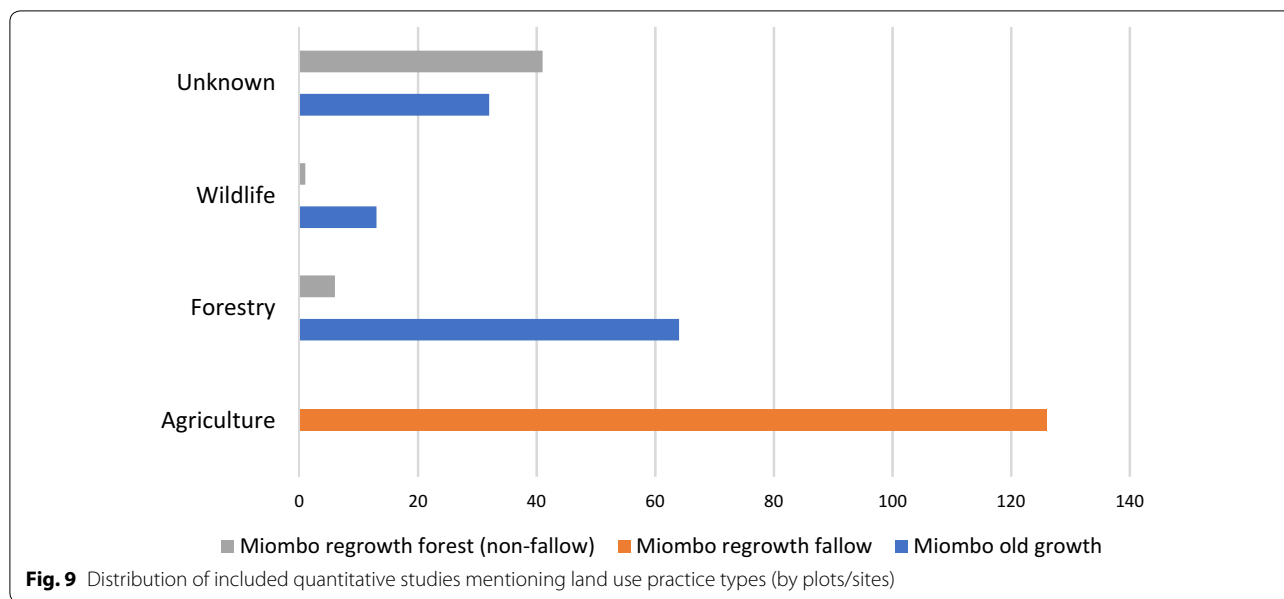
contribute to the global fight against climate change while providing development benefits to communities on the ground. Countries like Tanzania, Mozambique and Zambia have gone through REDD+ readiness and planning phases, and are moving towards the development and adoption of national REDD+ strategies [142–144]. It is important therefore that such initiatives take cognisance of the current dynamics in C stocks in miombo woodlands during their development phase. To some extent, data and information generated in the planning phases have been incorporated in country reports to UNFCCC and in some cases used to bolster regional climate change negotiations (see [145]).

Carbon stock recovery in re-growth woodland

The studies report sufficient data on trends in C stock recovery in re-growth miombo that could be analysed to assess possible differences in recovery trajectories on post-clearing re-growth and fallow re-growth sites. In shifting cultivation systems most fallow re-growth is converted back to cropland before the age of 30 years [96, 146–148]; reported declines in C stocks after 20 years would need further research.

Studies report C stock increments in young re-growth (< 15 years old) and for intermediate ages (15–40 years), but few data points for older trees. Chidumayo [84] found that stem density in re-growth miombo of 49 years was 13–25% of that in re-growth of 11 years and the decrease in stem density was attributed to competition in the intervening period. These changes often indicate a socio-economic portrait of the landscape born out

of the interplay between land use measures and decisions by people and governments [149, 150] and in the case of southern Africa, land contestations of 1990s and encroachments in response to Structural Adjustment Programmes (SAPs) of the same period have been behind forest loss in general [151]. New policy and management strategies are therefore required to reverse this negative trend if new initiatives, such as REDD+, are to achieve their objectives.

Effects of fire management on carbon stocks and dynamics

Wild fires affect carbon stocks and dynamics in miombo woodlands [25, 98] and there were studies reporting this effect. Previous findings indicate that production and C accumulation in miombo woodland is higher under fire protection and early burning than under late burning [11, 56, 84, 152]. However, complete fire protection is risky because accidental fires occurring under fire protection can find more fuel to burn and undo the gains made in carbon stocks accumulated over long periods. Chidumayo [56] reported that in a 36-year old fire protected re-growth plot, an accidental fire reduced carbon stocks to 13.9 Mg ha^{-1} compared to a stock of 72.5 Mg ha^{-1} that had accumulated under early burning. However, after 36 years of the experiment, both these carbon stocks were higher than that of 2.3 Mg ha^{-1} under late burning.

Limitations of the map

While our search strategy aimed to minimise publication bias by consulting a wide range of peer-reviewed and grey literature sources, we did not have the time nor

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resources to review studies in languages other than English. As such, we are likely to have missed relevant studies in Portuguese and other languages from the southern African region. The lack of systematic biomass assessments across the regions' climatic and environmental gradients, while accounting carefully for human intervention, is another important limiting factor.

Most of the data were chronosequence studies that used space for time and may have spatial confounding factors. In addition to conservation area status, data reported included age and type of re-growth (i.e. fallow re-growth or woodland re-growth) and cultivation period that provides information indicative of temporal trends in carbon stocks and sequestration.

Studies reported above- and below-ground carbon stocks in miombo woodlands in a wide variety of ways. Most studies estimated above-ground wood biomass using allometric models based on tree diameter measurements at breast height. These models ranged from non-linear power functions to linear logarithmic models and therefore the estimates may have contained biases due to the allometric model used. This would be a serious challenge for future anlaysis of reported data. Meta analysis of the data in these studies would require that all the data be converted to carbon units at the same spatial scale (e.g. Mg C ha^{-1}) using an appropriate equation [68].

Conclusions

Implications for research in the miombo and future systematic review topics

The systematic map reveals an inadequate evidence base to address the four questions originally posed in our protocol. An insufficient number of robust studies was found that meet our inclusion criteria from across the miombo region. There is a clear knowledge gap for Angola, northern Mozambique and the Democratic Republic of Congo, at least from the wide sources we consulted, and while we acknowledge that this may due in large part to language bias in the mainstream academic literature, it points to a need to focus on this region in future primary research. There was more literature on dry miombo sites compared with moist sites, and the latter may also be a useful focus for future research. The relative dearth of qualitative studies highlights a potential source of future work to develop policy based on community engagement in the miombo region.

Much further research is needed to understand C stocks and their trends in miombo old-growth woodland, because pooling the data is not sufficiently informative for localised management suggestions, given the variability (i.e., rainfall, aridity, soil depth and stand age) of miombo across the region. Understanding

miombo biomass stocks, losses and gains and carbon sequestration in light of the variability across the regional gradients is crucial for future studies. It would require better assessment of both above- and below-ground biomass across the region in a systematic way, accounting for spatial, climatic and land use differences.

In light of these findings, we suggest that future studies in miombo woodlands take longer term observational approaches with systematic, permanent sampling designs (versus chronosequence study designs). We also identify a few important phenomena pertinent to miombo woodland land use policy and management that would benefit from systematic review with meta analysis:

- Do carbon stocks in miombo woodlands return to previous levels after disturbance?
- What are the differences between carbon stocks in fallow re-growth sites and those in post-clearing re-growth sites, which appear to take longer to re-establish but reach higher levels?
- Is regrowth after agricultural fallowing slower than after clearing and are conservation areas adequately protecting miombo woodlands?
- Is controlled fire management, especially with early burning, a favourable management strategy for miombo woodlands to sequester and store carbon?

Additional files

Additional file 1. Literature search; showing literature sources, search strings, and keywords used.

Additional file 2. Study validity table; showing critical appraisal process.

Additional file 3. Additional information; showing the quantitative data used in the analysis.

Additional file 4. Excluded studies at full text and study appraisal levels.

Authors' contributions
Emmanuel Chidumayo (EC) carried out quantitative data analysis and drafted the manuscript, with additional inputs from JC, who coordinated the work, and IG, CM and GP. JC, DG, KYM, KBM, IG, RN, GK, CM and RN screened studies; and EC, JC, DG, KYM, KBM appraised the studies and extracted data. All authors read and approved the manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
All data generated or analysed during this study are included in this published article (and Additional files 1, 2, 3, 4) and most are publicly accessible. Some data that support the findings of this study are from older studies and are not publicly available. Other information and data needed are available from the corresponding author upon reasonable request.

Consent for publication
Not applicable.

Ethics approval and consent to participate
Not applicable.

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