MAPPING AGRICULTURAL SUITABILITY

A REVIEW OF APPROACHES TO SUPPORT THE ASSESSMENT OF SYNERGIES AND TRADE-OFFS BETWEEN AGRICULTURAL DEVELOPMENT AND MAINTAINING BIODIVERSITY AND ECOSYSTEM SERVICES

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Authors

Andrew Farrow, Sarah Darrah, Max Fancourt and Marieke Sassen

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UNEP World Conservation Monitoring Centre (UNEP-WCMC)
219 Huntingdon Road,
Cambridge CB3 0DL, UK
Tel: +44 1223 277314
www.unep-wcmc.org

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AEZ	Agro-Ecological Zoning
AHP	Analytical Hierarchy Process
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CGIAR	Consultative Group for International Agricultural Research
CLUE	Conversion of Land Use and its Effects
DRC	Democratic Republic of the Congo
DSSAT	Decision Support System for Agrotechnology Transfer
EPL	Economic Pressure on Land
FAO	Food and Agriculture Organization of the United Nations
FAO AEZ	FAO Agro-Ecological Zones
FAO GAEZ	FAO Global Agro-Ecological Zoning
GAEZ	Global Agro-Ecological Zoning
GCM	Global Circulation Models
GIS	Geographic Information System
GWR	Geographically Weighted Regression
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LU	Land Unit
MCDA	Multi-criteria Decision Analysis
PCA	Principal Components Analysis
UNEP	United Nations Environment Programme
UNEP-WCMC	United Nations Environment Programme – World Conservation Monitoring Centre
US	United States
WMO	World Meteorological Organization
Yp	Potential Yield
Yw	Water-limited Yield

Executive Summary

This report provides an overview of existing approaches to mapping agricultural suitability, including review of the underlying data, at different scales. Mapping land use suitability can help identify the best places for different future land uses and support a more efficient and effective use of resources and energy to satisfy changing patterns of human consumption, to slow global warming and to reduce the rate of loss of ecosystem services and biodiversity.

The review seeks to better understand the spatial scales and timescales considered by existing approaches to map agricultural suitability and the criteria and methods used to asses land suitability for different crops or land use types. Published approaches were reviewed using a systematic literature review method, followed by a more targeted literature search for widely used approaches. 136 papers were classified following key questions relating to the purpose and methodology of the review. This review forms part of a suite of technical reviews, including reviews on ecosystem services and biodiversity mapping, scenario development and land use change models, these documents can be used, along with a Capacity Development Assessment Tool, to support an ecosystem-based approach to agricultural development policy and land use planning.

In our analysis, priority was given to studies that developed or used global, continental or regional suitability assessments. Particular attention is paid to assessing the potential trade-offs between agricultural development (expansion and intensification) on biodiversity and ecosystem services at global and continental scales, as these studies provided the most widely applicable methods and lessons.

The review of methods yielded five main approaches to mapping agricultural suitability.

Approaches based on plant physiology:

1. Biophysical characterisation of pre-defined zones
2. Empirical models
   - Ecological niche models
3. Process-based models
   - Site-based crop growth simulation models
   - Agro-ecosystem models
   - Agro-Ecological Zones approach

Approaches that also consider socioeconomic components of suitability:

4. Socioeconomic and biophysical characterisation of pre-defined zones
5. Coupled socioeconomic and biophysical models

The vast majority of global and continental studies reviewed use process-based approaches, incorporating knowledge on plant physiology and responses to abiotic stresses, the Food and Agricultural Organisation of the United Nations (FAO) Agro-Ecological Zoning (AEZ) approach being the most common of these. Socioeconomic constraints affect the likelihood that a particular land use will be encountered at a particular place and at a particular time, in spite of its biophysical suitability. In order to assess the likelihood of agriculture at any particular place and time, agronomic suitability assessments using the AEZ methodology need to be complemented with additional biophysical, socioeconomic or institutional constraints and/or incentives that may affect potential land use. Approaches using inductive reasoning, such as ecological niche models, infer agricultural suitability from existing spatial and temporal vegetation patterns. They are useful for visualising potential land use conflicts and implicitly take into account the likelihood of agriculture, but do not consider many of the socioeconomic factors that are known to affect land use choices.

Studies that combine actual cropping systems, suitability for distinct crops, local factors that favour particular crops or land uses and scenarios of global demand would therefore appear to offer the most complete assessment of the likelihood of land conversion to different crop types or from non-agriculture to agriculture or to agricultural intensification.

Suitability for agriculture can be calculated for any location or pixel for which data is available (such as in Global Agro-Ecological Zoning; GAEZ). Studies that defined zones mainly did so to help design future research or as a communication tool. Zones often mask the heterogeneity of factors that are important for determining agricultural suitability and the likelihood of land conversion or land degradation.

Global and continental studies at very high resolution (<5 km²) are still uncommon, mainly due to the lack of extremely high resolution climate data or of data on functional soil properties. Common measures of suitability relate to plant biomass, or attainable yield, both of which are plot level outputs. However when assessing suitability for medium resolutions (5–50 km²), each pixel could represent a farming system or a landscape instead of a single crop, but there are as yet no measures of suitability that consider such system levels.

There are two important objectives for assessing the suitability of land for agriculture. The first is to provide information that can be used to calculate potential agricultural production, while the second is to determine the likelihood of conversion of land to and from agriculture or the likelihood of intensification, based on suitability and drivers of land use change. The first will help to (i) evaluate trade-offs or synergies between biodiversity and ecosystem services values and agricultural production in scenarios where suitable but unused areas are converted to agriculture, (ii) identify areas that may have higher value for biodiversity and ecosystem services if restored from their current unsuitable use, and (iii) identify local and regional yield gaps (the difference between actual yields and potential yields) that are important indicators of the efficiency of agriculture. Such analyses can inform decision-making with the most efficient use of land for agriculture and other land uses providing ecosystem services. The second aids in developing maps of potential increasing or decreasing "pressures" on biodiversity and ecosystem services from likely future developments, to support policy regulation in mitigating the pressures on certain high value areas.

This review highlights the importance of taking into account the dynamism of factors that affect the biophysical suitability of land for agriculture and the likelihood of land being used for agricultural production. The main biophysical factor affecting future agricultural suitability is climate change. Process-based modelling is used to estimate these changes and their impacts. However, the range of contextual factors that 'cause' land to be used in a certain way or for certain crops is possibly the biggest hurdle for both approaches that use process-based and empirical models.

Finally, this report shows that with better access to data and wider sharing of methods, there has been an increasing number of assessments of agricultural suitability; a welcome development given the global pressure on land for agriculture. The studies in this review show there are also many novel methods at the national and local levels related to land use planning which could be incorporated into global and continental studies. The challenge will be to reconcile decision-making at multiple levels, volatility of macro-economic drivers of land use, and fundamental changes to the biophysical environment.

Résumé

Le présent rapport propose une vue d'ensemble des approches existantes en matière de cartographie de la vocation agricole des terres y compris un examen des données sous-jacentes, à différentes échelles. Cartographier l'aptitude des sols aux cultures peut permettre d'identifier les meilleurs endroits où les terres pourront être utilisées à des fins diverses et soutenir une utilisation plus efficace des ressources et de l'énergie, en vue de répondre à l'évolution des modèles de consommation humaine, de freiner le réchauffement climatique et de réduire le taux de perte au niveau des services écosystémiques et de la biodiversité.

Cet examen cherche à mieux comprendre les échelles spatiales et temporelles utilisées par les approches existantes afin de cartographier la vocation agricole des terres, et les méthodes et critères permettant d'évaluer l'aptitude des terres à différentes cultures ou à divers types d'utilisation. Les stratégies publiées ont été révisées à l'aide d'une méthode d'analyse documentaire systématique, suivie d'une recherche documentaire plus ciblée, axée sur les approches les plus utilisées. Quelque 136 documents ont été classifiés suivant les questions clés relatives à l'objet et à la méthodologie de l'examen. Celui-ci fait partie intégrante d'une série de révisions techniques, y compris de révisions portant sur la cartographie des services écosystémiques et de la biodiversité, l'élaboration de scénarios et les modèles de changement d'utilisation des terres. Couplés d'un outil d'évaluation du développement des capacités, ces documents peuvent soutenir une stratégie de développement agricole et de planification de l'utilisation des terres axée sur l'écosystème.

Dans notre analyse, nous avons donné la priorité aux études ayant élaboré ou exploité les évaluations de l'aptitude des terres réalisées à l'échelle mondiale, continentale ou régionale. Nous avons prêté une attention particulière aux compromis éventuels entre le développement agricole (expansion et intensification) et la biodiversité et les services écosystémiques à l'échelle mondiale et continentale, étant donné que ces études ont fourni les enseignements et les méthodes les plus largement applicables.

L'examen des méthodes utilisées dans les évaluations à l'échelle mondiale et continentale a permis d'élaborer cinq approches principales de cartographie de la vocation agricole des sols :

Les approches axées sur la physiologie des plantes :

1. Caractérisation biophysique de zones prédéfinies

2. Modèles empiriques
   - Modèles utilisant les niches écologiques

3. Modèles axés sur les processus
   - Modèles de simulation de la croissance des cultures sur site
   - Modèles agro-écosystémiques
   - Approche par zone agro-écologique (ZAE)

Les stratégies tenant également compte des facteurs socio-économiques déterminant l'aptitude des terres :

4. La caractérisation socio-économique et biophysique de zones prédéfinies

5. Combinaison des modèles socio-économiques et biophysiques

La grande majorité des études mondiales et continentales examinées reposent sur des approches axées sur les processus, intégrant des informations relatives à la physiologie des plantes et à la lutte contre les agressions abiotiques, l'approche par zone agro-écologique adoptée par l'Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO) étant la plus couramment utilisée. Les contraintes socio-économiques affectent la probabilité que des terres soient utilisées dans un lieu précis à un moment précis, en dépit de l'aptitude biophysique de cet endroit. Afin d'évaluer la probabilité que des activités agricoles soient menées dans un lieu et à un moment particulier, les évaluations d'aptitude agronomique utilisant l'approche ZAE doivent tenir compte des contraintes biophysiques, socio-économiques ou institutionnelles supplémentaires et/ou des incitations pouvant affecter l'utilisation éventuelle des terres. Les approches ayant recours à l'induction, telles que les modèles utilisant les niches écologiques, déduisent le potentiel agricole de modèles de végétation spatio-temporels existants. Elles sont utiles pour visualiser les éventuels conflits en matière d'utilisation des terres et prennent en compte de façon implicite la probabilité que des activités agricoles y soient réalisées, mais elles ignorent de nombreux facteurs socio-économiques connus pour affecter les choix d'utilisation des terres.

Les études combinant les systèmes de culture actuels, l'aptitude des terres à des cultures distinctes, les facteurs locaux favorisant des cultures particulières ou l'utilisation des terres et des scénarios de demande mondiale peuvent par conséquent émerger, offrant l'évaluation la plus complète de la probabilité que des terres soient converties à différents types de culture ou que des terres non cultivées soient utilisées à des fins d'agriculture, ou d'intensification agricole.

La vocation agricole peut être calculée pour tout lieu ou pixel pour lequel des données sont disponibles, tel que dans les zones agro-écologiques mondiales (GAEZ). Les études ayant défini des zones ont principalement utilisé ce procédé comme outil de communication ou afin d'aider à concevoir une prochaine étude. Les zones cachent souvent l'hétérogénéité des facteurs qui sont néanmoins importants pour déterminer le potentiel agricole et la probabilité de conversion et de dégradation des terres.

Les études de très haute résolution (< 5 km^2) menées à l'échelle mondiale et continentale sont toujours rares, principalement du fait du manque de données climatiques de très haute résolution ou d'informations relatives aux propriétés fonctionnelles des terres. Les mesures courantes d'aptitude des sols portent sur la biomasse végétale, ou le rendement possible, lesquels constituent des extrants au niveau des parcelles. Cependant, lors de l'évaluation de l'aptitude des terres pour des résolutions moyennes (5–50 km^2), chaque pixel peut représenter un système agricole ou un paysage au lieu d'une seule culture, mais il n'existe encore aucune mesure d'aptitude des sols prenant en compte de tels niveaux de systèmes.

L'évaluation de l'aptitude des terres à l'agriculture comporte deux objectifs majeurs. Le premier est de fournir des informations pouvant être utilisées pour calculer la production agricole éventuelle, alors que le deuxième consiste à déterminer la probabilité que des terres soient converties en terres agricoles ou que des terres agricoles cessent d'être exploitées, ou la probabilité de l'intensification agricole, en s'appuyant sur l'aptitude des sols et les facteurs déterminant le changement d'utilisation des terres. Le premier objectif contribuera à : (i) évaluer les compromis ou les synergies entre les valeurs de la biodiversité et des systèmes écosystémiques, et la production agricole, dans des situations où des zones adaptées mais inutilisées sont converties en terres agricoles ; (ii) identifier les zones pouvant présenter une valeur supérieure en termes de biodiversité et de services écosystémiques si ces terres actuellement impropres à l'exploitation sont revalorisées, et (iii) identifier les écarts de rendements à l'échelle locale et régionale (la différence entre les rendements réels et potentiels) qui constituent d'importants indicateurs de l'efficacité de l'agriculture. Ces analyses peuvent éclairer les prises de décision grâce à une meilleure utilisation des terres cultivables et à une variété d'autres utilisations des terres offrant des systèmes écosystémiques. Le deuxième objectif facilite la cartographie de l'augmentation et de la diminution éventuelles de « pressions » pesant sur la biodiversité et les services écosystémiques à partir de développements futurs vraisemblables, en vue de soutenir la réglementation politique visant à atténuer les pressions exercées sur certaines zones de grande valeur.

Cet examen souligne l'importance de prendre en compte le dynamisme des facteurs affectant l'aptitude biophysique des terres à l'agriculture et la probabilité que ces dernières soient destinées à la production agricole. Le principal facteur biophysique affectant la vocation agricole des terres est le changement climatique. La modélisation axée sur les processus est utilisée pour estimer ces changements et leurs impacts. Cependant, l'ensemble de facteurs contextuels « à l'origine » d'une utilisation particulière des terres ou de leur exploitation pour certaines cultures est probablement la difficulté rencontrée la plus importante lorsque l'on utilise des modèles empiriques et axés sur les processus.

Enfin, le présent rapport montre que grâce à un meilleur accès aux données et à un plus grand partage des méthodes, de plus en plus d'évaluations de la vocation agricole des terres ont été réalisées, un développement bienvenu étant donné la pression mondiale exercée sur les terres agricoles. Les études abordées dans cette analyse montrent qu'il existe également de nombreuses méthodes nouvelles à l'échelle locale et nationale portant sur la planification de l'utilisation des terres et qui pourraient être intégrées à des études mondiales et continentales. Le défi sera de concilier la prise de décision à plusieurs niveaux, la volatilité des facteurs macroéconomiques déterminant l'exploitation des sols et les changements fondamentaux de l'environnement biophysique.

Resumen

Este informe ofrece una panorámica de los enfoques actuales con relación a la cartografía de la aptitud agrícola, en la que se incluye una revisión de los datos subyacentes a diversas escalas. La cartografía de la aptitud del uso de la tierra puede facilitar la identificación de los lugares más apropiados para diversos usos de la tierra en un futuro y respaldar una utilización de los recursos y la energía más eficaz y eficiente con el fin de satisfacer los modelos cambiantes de consumo humano, ralentizar el calentamiento del planeta y reducir la tasa de pérdida de servicios de los ecosistemas y biodiversidad.

El propósito de la revisión es proporcionar una mejor comprensión de las escalas espaciales y temporales contempladas en los enfoques que se aplican a la cartografía de la aptitud agrícola en la actualidad, así como de los criterios y métodos utilizados para evaluar la aptitud de la tierra para diferentes tipos de cultivos o usos. En el examen de los enfoques publicados se empleó un método sistemático de revisión de la bibliografía, seguido de una búsqueda de documentación más específica sobre los enfoques más extendidos. Se clasificaron 136 documentos a partir de una serie de cuestiones clave relativas al propósito y la metodología de la revisión. Este examen forma parte de un conjunto de revisiones técnicas, entre otras, relativas a la cartografía de los servicios de los ecosistemas y la biodiversidad, al desarrollo de escenarios y a los modelos de cambio en el uso de la tierra. Junto con la herramienta de evaluación del desarrollo de la capacidad, estos documentos pueden utilizarse para respaldar un enfoque de las políticas de desarrollo agrícola y de la planificación del uso de la tierra basado en los ecosistemas.

En nuestro análisis se dio prioridad a los estudios que desarrollaban o empleaban evaluaciones de la aptitud a escala regional, continental o mundial. Estos estudios abordaban los métodos y las lecciones de mayor ámbito de aplicación, por lo que se prestó una atención especial a la evaluación de las posibles compensaciones entre el desarrollo agrícola (expansión e intensificación) con relación a la biodiversidad y los servicios de los ecosistemas en las esferas continental y mundial.

La revisión de los métodos empleados en las evaluaciones continentales y mundiales dio lugar a cinco enfoques principales para la cartografía de la aptitud agrícola:

Enfoques basados en la fisiología vegetal:

1. Caracterización biofísica de zonas predeterminadas

2. Modelos empíricos
   - Modelos de nicho ecológico

3. Modelos basados en el proceso
   - Modelos de simulación del crecimiento de los cultivos basados en el emplazamiento
   - Modelos de ecosistemas agrícolas
   - Enfoque de las zonas agroecológicas

Enfoques que también tienen en cuenta los componentes socioeconómicos de la aptitud:

4. Caracterización socioeconómica y biofísica de zonas predeterminadas

5. Modelos socioeconómicos y biofísicos acoplados

La gran mayoría de los estudios continentales y mundiales analizados aplican enfoques basados en el proceso, que incorporan el conocimiento sobre la fisiología vegetal y las respuestas a los estreses abióticos. El más común de estos estudios es el Proyecto de Zonas Agroecológicas de la Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO, por sus siglas en inglés). Las limitaciones socioeconómicas determinan la probabilidad de encontrar un uso específico de la tierra en un lugar y un momento concretos, con independencia de su aptitud biofísica. A efectos de evaluar la probabilidad de que se dé un uso agrícola en cualquier lugar y momento concretos, las evaluaciones de la aptitud agronómica basadas en la metodología de las zonas agroecológicas deben complementarse con otras limitaciones biofísicas, socioeconómicas o institucionales, o bien con incentivos que puedan afectar al uso potencial de la tierra. En los enfoques que aplican un razonamiento inductivo, tales como los modelos de nicho ecológico, la aptitud agrícola se deduce a partir de los patrones de vegetación temporales y espaciales existentes. Si bien estos resultan útiles para visualizar los conflictos entre los usos potenciales de la tierra y considerar de forma implícita la probabilidad de un uso agrícola, no tienen en cuenta muchos de los factores socioeconómicos que condicionan las decisiones sobre el uso de la tierra.

Los estudios que combinan los sistemas de cultivo vigentes, la aptitud para los distintos cultivos, los factores locales que favorecen unos cultivos o usos de la tierra específicos y los escenarios de demanda mundial parecen, por tanto, ofrecer la evaluación más completa de la probabilidad de conversión de la tierra hacia diferentes tipos de cultivos o de un uso no agrícola a uno agrícola, o bien a la intensificación de la agricultura.

Es posible calcular la aptitud agrícola de cualquier zona o píxel del que se disponga de datos (como en los sistemas mundiales de zonificación agroecológica [GAEZ]). Los estudios que han establecido las zonas lo han hecho fundamentalmente a fin de ayudar a diseñar la investigación futura o servir de herramienta de comunicación. El establecimiento de zonas suele ocultar la heterogeneidad de los factores que resultan relevantes para determinar la aptitud agrícola y la probabilidad de conversión o degradación de la tierra.

Los estudios continentales o mundiales con una resolución muy alta (<5 km^2) son todavía poco habituales, lo cual se debe principalmente a la carencia de datos climáticos con una resolución extremadamente alta o de datos relativos a las propiedades funcionales del suelo. Las mediciones de la aptitud más comunes están relacionadas con la biomasa vegetal o con el rendimiento factible, y ambos ofrecen resultados por parcelas de muestreo. No obstante, cuando se evalúa la aptitud para resoluciones medias (5-50 km^2), cada píxel podría representar un sistema agrícola o un paisaje en lugar de un único cultivo, pero siguen sin existir mediciones de la aptitud que tengan en cuenta tales niveles del sistema.

La evaluación de la aptitud de la tierra para fines agrícolas persigue dos objetivos importantes. El primero es proporcionar información que pueda usarse para calcular la producción agrícola potencial, mientras que el segundo es determinar la probabilidad de conversión de la tierra para su uso agrícola o viceversa y la probabilidad de la intensificación agrícola, sobre la base de su aptitud y de los factores que impulsan el cambio de uso de la tierra. El primer objetivo contribuirá a i) evaluar las compensaciones o sinergias entre los valores de la biodiversidad y los servicios de los ecosistemas y la producción agrícola en escenarios donde las zonas aptas pero sin utilizar se convierten en tierras agrícolas; ii) identificar las zonas que pueden presentar un valor mayor para la biodiversidad y los servicios de los ecosistemas si se corrige su uso inadecuado actual; e iii) identificar las brechas de rendimiento (la diferencia entre el rendimiento efectivo y el potencial) en el ámbito local y regional, las cuales constituyen indicadores relevantes de la eficiencia de la agricultura. Estos análisis pueden servir para fundamentar la adopción de decisiones a partir de información sobre el uso más eficiente de la tierra para fines agrícolas y otros usos que proporcionan servicios de los ecosistemas. El segundo objetivo contribuye a la elaboración de mapas de las posibles «presiones», crecientes o decrecientes, sobre la biodiversidad y los servicios de los ecosistemas a partir de avances posibles en el futuro, a fin de respaldar una política normativa relativa a la mitigación de las presiones en algunas áreas de gran valor.

Esta revisión destaca la importancia de considerar el dinamismo de los factores que afectan a la aptitud biofísica de la tierra para su uso agrícola y la probabilidad de que la tierra se use con fines de producción agrícola. El cambio climático es el factor biofísico que tendrá una mayor repercusión en la aptitud agrícola de la tierra en un futuro. La elaboración de modelos basados en el proceso se utiliza para calcular estos cambios y sus efectos. No obstante, la variedad de factores contextuales que «causan» que la tierra se utilice de un modo concreto o para ciertos cultivos es, posiblemente, el mayor obstáculo al que se enfrentan los dos enfoques que emplean modelos empíricos y basados en el proceso.

Por último, este informe revela que el mejor acceso a los datos y la mayor puesta en común de los métodos han propiciado un número creciente de evaluaciones de la aptitud agrícola, un avance muy positivo dada la presión mundial que existe sobre el uso agrícola de la tierra. Los estudios incluidos en esta revisión muestran asimismo la existencia de numerosos métodos novedosos a nivel local y nacional relacionados con la planificación del uso de la tierra que pueden incorporarse a los estudios continentales y mundiales. El desafío consistirá en conciliar la adopción de decisiones en niveles múltiples, la volatilidad de los factores macroeconómicos que influyen en el uso de la tierra y los cambios fundamentales en el entorno biofísico.

Sumário executive

Este relatório fornece uma visão geral das abordagens existentes para o mapeamento de aptidão agrícola, incluindo a revisão dos dados subjacentes, em diferentes escalas. Mapeamento do uso do solo adequação pode ajudar a identificar os melhores lugares para diferentes futuros usos do solo e apoiar uma utilização mais eficiente e eficaz de recursos e energia para satisfazer as mudanças nos padrões de consumo humano, o aquecimento global lento e reduzir a taxa de perda dos serviços dos ecossistemas e da biodiversidade.

A revisão visa compreender melhor as escalas espaciais e prazos considerados pelas abordagens existentes para mapear aptidão agrícola e os critérios e métodos utilizados para adequação jumentos terra para diferentes culturas ou tipos de uso da terra. abordagens publicados foram revistos utilizando um método de revisão sistemática da literatura, seguido por uma pesquisa mais direcionada literatura para abordagens amplamente utilizados. 136 artigos foram classificados seguintes questões-chave relacionadas com a finalidade ea metodologia da avaliação. Esta avaliação faz parte de um conjunto de revisões técnicas, incluindo comentários sobre os serviços dos ecossistemas e mapeamento da biodiversidade, desenvolvimento de cenários e modelos de mudança de uso da terra, estes documentos podem ser utilizados, juntamente com uma capacidade de Desenvolvimento Ferramenta de Avaliação, para apoiar uma abordagem baseada nos ecossistemas política de desenvolvimento agrícola e ordenamento do território.

Em nossa análise, foi dada prioridade aos estudos que se desenvolveram ou usados avaliações globais, continentais ou regionais de adequação. É dada especial atenção à avaliação dos potenciais soluções de compromisso entre o desenvolvimento agrícola (expansão e intensificação) sobre biodiversidade e serviços ambientais em escalas globais e continentais, como esses estudos forneceram os métodos e as lições mais amplamente aplicáveis.

A revisão dos métodos utilizados nas avaliações globais e continentais escala rendeu cinco abordagens principais para o mapeamento de aptidão agrícola:

Abordagens com base em fisiologia vegetal:

1. caracterização biofísica das zonas pré-definidas

2. modelos empíricos
   - modelos de nicho ecológico

3. Modelos baseadas em processos
   - modelos de simulação de crescimento da cultura baseada em site
   - modelos agroecossistema
   - zonas agro-ecológicas aproximar

Abordagens que também consideram componentes socioeconômicos de adequação:

4. Caracterização Socioeconômica e biofísica das zonas pré-definidas

5. modelos socioeconómicos e biofísicos Coupled

A grande maioria dos estudos globais e continentais avaliação utilizam abordagens baseadas em processos, incorporando os conhecimentos sobre a fisiologia da planta e respostas a estresses abióticos, a Food and Agricultural Organisation das United Nations (FAO) Zoneamento Agroecológico (AEZ) sendo o mais comum destes. constrangimentos socioeconômicos afetam a probabilidade de que um uso da terra particular será encontrado em um determinado lugar e em um determinado momento, apesar de sua adequação biofísica. A fim de avaliar a probabilidade de a agricultura em qualquer lugar e tempo, as avaliações de aptidão agronômicos, utilizando a metodologia AEZ precisam ser complementadas com restrições biofísicas, socioeconômicas e institucionais adicionais e / ou incentivos que podem afetar uso potencial da terra. Abordagens utilizando o raciocínio indutivo, tais como modelos de nicho ecológico, inferir aptidão agrícola a partir de padrões de vegetação espaciais e temporais existentes. Eles são úteis para a visualização de potenciais conflitos de uso da terra e, implicitamente, ter em conta a probabilidade de agricultura, mas não consideram muitos dos fatores socioeconômicos que são conhecidos por afetar o uso escolhas de terra.

Estudos que combinam sistemas de cultivo reais, aptidão para culturas distintas, fatores locais que favorecem culturas específicas ou usos da terra e cenários de demanda mundial se, portanto, para oferecer a avaliação mais completa do risco de conversão da terra para diferentes tipos de culturas ou de não-agrícola para a agricultura ou para a intensificação da agricultura.

Aptidão para a agricultura pode ser calculada para qualquer local ou de pixel para os quais há dados disponíveis (como em Global Zoneamento Agro-ecológico; GAEZ). Estudos que definiram zonas, principalmente, fez isso para ajudar a projetar futuras pesquisas ou como uma ferramenta de comunicação. Zonas muitas vezes mascarar a heterogeneidade dos fatores que são importantes para determinar a aptidão agrícola e da probabilidade de conversão de terras ou a degradação da terra.

estudos globais e continentais em resolução muito alta (<5 km^2) ainda são incomuns, principalmente devido à falta de dados sobre o clima extremamente alta resolução ou de dados sobre as propriedades funcionais do solo. medidas comuns de adequação relacionar para plantar biomassa, ou o rendimento atingível, ambos os quais são saídas de nível de enredo. No entanto, quando a avaliação da aptidão para resoluções médios (5-50 km^2), cada pixel pode representar um sistema de agricultura ou uma paisagem em vez de uma única cultura, mas há ainda nenhuma medida de adequação que consideram tais níveis do sistema.

Existem dois objectivos importantes para avaliar a adequação de terras para a agricultura. O primeiro é fornecer informação que pode ser usada para calcular a produção agrícola potencial, enquanto a segunda é determinar a probabilidade de conversão de terras para e proveniente da agricultura ou a probabilidade de intensificação, com base na aptidão e motores de mudança no uso da terra. O primeiro vai ajudar a (i) avaliar os trade-offs ou sinergias entre os valores de biodiversidade e serviços ambientais ea produção agrícola em cenários onde as áreas adequadas, mas não utilizados são convertidos para a agricultura, (ii) identificar as áreas que podem ter maior valor para a biodiversidade e serviços ecossistêmicos se restaurado a partir de seu uso impróprio atual, e (iii) identificar as lacunas de rendimento locais e regionais (a diferença entre os rendimentos reais e dos rendimentos potenciais) que são importantes indicadores da eficiência da agricultura. Tais análises podem informar a tomada de decisão com o uso mais eficiente da terra para a agricultura e outros usos da terra prestação de serviços ecossistêmicos. A segunda auxilia no desenvolvimento de mapas de potencial de aumentar ou diminuir "pressões" sobre biodiversidade e serviços ecossistêmicos de desenvolvimentos futuros prováveis, para apoiar a regulação política para atenuar as pressões sobre certas áreas de alto valor.

Esta avaliação destaca a importância de se levar em conta o dinamismo dos fatores que afetam a adequação biofísica da terra para a agricultura e a probabilidade de terra a ser utilizada para a produção agrícola. O principal fator que afeta biofísico futura aptidão agrícola é a mudança climática. modelagem baseada em processo é utilizada para estimar essas mudanças e seus impactos. No entanto, a gama de factores contextuais que a terra "causa" para ser usado em uma determinada maneira ou para certas culturas é possivelmente o maior obstáculo para ambas as abordagens que usam modelos empíricos baseado em processos e.

Finalmente, este relatório mostra que, com melhor acesso aos dados e uma maior partilha de métodos, tem havido um número crescente de avaliações de aptidão agrícola; uma evolução positiva, dada a pressão global sobre a terra para a agricultura. Os estudos nesta revisão mostra também existem muitos novos métodos nos níveis nacionais e locais relacionadas com o ordenamento do território que poderiam ser incorporados em estudos globais e continentais. O desafio será o de conciliar a tomada de decisão em vários níveis, a volatilidade dos motoristas macro-econômicas de uso da terra e mudanças fundamentais no ambiente biofísico.

Управляющее резюме

В настоящем докладе содержится обзор существующих подходов к отображению сельскохозяйственной пригодности, включая обзор основных данных, в разных масштабах. Картирование землепользования пригодность может помочь определить лучшие места для различных будущих видов землепользования и поддержки более эффективного и рационального использования ресурсов и энергии для удовлетворения меняющихся моделей потребления человеком, медленного глобального потепления и снижения темпов утраты экосистемных услуг и биоразнообразия.

Обзор стремится лучше понять пространственные масштабы и временные рамки, рассмотренные существующие подходы к карте сельскохозяйственной пригодности и критерии и методы, используемые для оценки пригодности земель для различных культур или видов землепользования. Опубликованные подходы были рассмотрены с помощью систематического метода обзора литературы, а затем более целенаправленного поиска литературы для широко используемых подходов. 136 статей были классифицированы следующие ключевые вопросы, касающиеся цели и методологии обзора. Данный обзор является частью набора технических обзоров, в том числе мнения об экосистемных услуг и картирования биоразнообразия, разработки сценариев и моделей изменения землепользования, эти документы могут быть использованы, а также потенциала развития инструмент оценки, для поддержки экосистемного подхода, основанного на политика развития сельского хозяйства и планирования землепользования.

В нашем анализе, приоритетное внимание было уделено исследованиям, которые разработаны или используются глобальные, континентальные или региональные оценки пригодности. Особое внимание уделяется оценке потенциальных компромиссов между сельскохозяйственным развитием (расширение и углубление) по биоразнообразия и экосистемных услуг на глобальном и континентальном масштабах, так как эти исследования послужили наиболее широко применяемые методы и уроки.

Обзор методов, используемых в глобальных и континентальных оценок масштаба дали пять основных подходов к отображению сельскохозяйственной пригодности:

Подходы, основанные на физиологии растений:

1. Биофизическое характеристика предварительно определенных зон

2. Эмпирические модели
   - Экологические модели ниши

3. Модели процессов на основе
   - Сайт на основе имитационных моделей роста культур
   - модели агроэкосистемных
   - агроэкологических зон приближения

Подходы, которые также рассмотреть вопрос о социально-экономических составляющих пригодности:

4. Социально-экономические и биофизические характеристики предварительно определенных зон

5. Сопряженные социально-экономические и биофизические модели

Подавляющее большинство мировых и континентальных исследований рассмотрено использование процесса на основе подходов, включая знания о физиологии растений и ответы на абиотическим стрессам подход, Продовольственная и сельскохозяйственная организация Объединенных Наций (ФАО) агроэкологического зонирования (AEZ) является наиболее распространенным из этих. Социально-экономические ограничения влияют на вероятность того, что конкретное использование земли будет встречаться в определенном месте и в определенное время, несмотря на его биофизической пригодности. Для того чтобы оценить вероятность сельского хозяйства в любом конкретном месте и времени, агрономические оценки пригодности с использованием методологии AEZ должны быть дополнены дополнительными биофизических, социально-экономических и институциональных ограничений и / или стимулов, которые могут повлиять на потенциальное использование земли. Подходы с использованием индуктивного рассуждения, такие как модели экологической ниши, выводим сельскохозяйственной пригодности из существующих пространственных и временных закономерностей растительности. Они полезны для визуализации потенциальных конфликтов землепользования и неявно учитывают вероятность сельского хозяйства, но не учитывают многих социально-экономических факторов, которые, как известно, влияют на выбор земельных использования.

Исследования, которые сочетают в себе фактические систем земледелия, пригодность для различных культур, местные факторы, которые благоприятствуют конкретных культур или землепользования и сценарии глобального спроса будет, поэтому, по всей видимости предложить наиболее полную оценку вероятности конверсии земель для различных видов сельскохозяйственных культур или из несельскохозяйственных сельскому хозяйству или интенсификации сельского хозяйства.

Пригодность для сельского хозяйства можно рассчитать для любого местоположения или пикселя, для которых имеются данные (например, в Глобальной агроэкологического зонирования; GAEZ). Исследования, в которых определенные зоны в основном делали это, чтобы помочь разработать будущие исследования или в качестве средства коммуникации. Зоны часто маскируют разнородность факторов, которые имеют важное значение для определения пригодности сельскохозяйственных и вероятность превращения земель или деградации земель.

Глобальные и континентальные исследования с очень высоким разрешением (<5 км^2), все еще редкость, в основном из-за отсутствия данных о климате чрезвычайно высокого разрешения или данных о функциональных свойств почвы. Общие меры пригодности относятся к переработке биомассы, или достижимый выход, оба из которых являются выходами уровня участка. Однако при оценке пригодности для резолюций среднего (5-50 км^2), каждый пиксель может представлять собой систему земледелия или пейзаж вместо одного урожая, но пока еще никаких мер пригодности, которые рассматривают такие уровни системы.

Есть две важные цели для оценки пригодности земель для сельского хозяйства. Во-первых, предоставить информацию, которая может быть использована для расчета потенциального сельскохозяйственного производства, а во-вторых, чтобы определить вероятность превращения земли и от сельского хозяйства или вероятности интенсификации, основанный на пригодности и водителей изменения землепользования. Первый поможет (I) оценку компромиссов или синергии между ценностями биоразнообразия и экосистемных услуг и сельскохозяйственного производства в сценариях, где подходящие, но неиспользуемые участки преобразуются в сельское хозяйство, (б) определить области, которые могут иметь большее значение для биоразнообразия и экосистемных услуг если они восстановлены от их текущего использования неподходящей, и (III) определение местных и региональных пробелов урожайности (разница между фактическими выходами и потенциальной урожайности), которые являются важными показателями эффективности сельского хозяйства. Такой анализ может информировать принятия решений наиболее эффективного использования земли для сельского хозяйства и других видов землепользования, обеспечение экосистемных услуг. Второй помогает в разработке карт потенциального увеличения или уменьшения "давления" на биоразнообразия и экосистемных услуг, от возможных будущих событий, для поддержки регулирования политики в целях смягчения давления на определенных областях с высокой добавленной стоимостью.

В этом обзоре подчеркивается важность учета динамизм факторов, влияющих на биофизической пригодности земель для сельского хозяйства и вероятность земель, используемых для сельскохозяйственного производства. Основным фактором, влияющим на биофизических будущую сельскохозяйственную пригодность является изменение климата. Процесс моделирования на основе используется для оценки этих изменений и их последствий. Тем не менее, ряд контекстных факторов, потому что "земля будет использоваться определенным образом или для определенных культур, возможно, является самым большим препятствием для обоих подходов, которые используют процесс на основе и эмпирических моделей.

Наконец, этот отчет показывает, что более широкий доступ к данным и более широкого совместного использования методов, наблюдается все большее число оценок сельскохозяйственной пригодности; позитивным событием, учитывая глобальное давление на землю для сельского хозяйства. Исследования в этом обзоре, показывают, есть также много новых методов на национальном и местном уровнях, связанных с планированием землепользования, которые могут быть включены в глобальные и континентальных исследований. Задача заключается в том, чтобы согласовать процесс принятия решений на различных уровнях, волатильности макро-экономических факторов землепользования, а также фундаментальных изменений в биофизической среды.

هناك نوعان من الأهداف الهامة لتقييم مدى ملاءمة الأرض للزراعة. الأول هو توفير المعلومات التي يمكن استخدامها لحساب الإنتاج الزراعي محتمل، في حين أن الثانية هي تحديد احتمال تحويل الأراضي إلى ومن الزراعة أو احتمال تكثيف، على أساس ملاءمة وعوامل التغيير في استخدام الأراضي. أول سيساعد على (ط) تقييم المقايضات أو التآزر بين قيم التنوع البيولوجي وخدمات النظم الإيكولوجية والإنتاج الزراعي في سيناريوهات حيث يتم تحويل مناطق مناسبة ولكن غير المستخدمة للزراعة، (ب) تحديد المجالات التي قد يكون لها قيمة أعلى للتنوع البيولوجي وخدمات النظام الإيكولوجي إذا استعادة من استخدام غير مناسب الحالي، و (ج) تحديد الثغرات العائد المحلية والإقليمية (الفرق بين عوائد الفعلية والعوائد المحتملة) التي هي مؤشرات هامة كفاءة الزراعة. ويمكن لهذه التحليلات إبلاغ صنع القرار مع أكفأ استخدام الأراضي للزراعة ويستخدم توفير خدمات النظم الإيكولوجية البرية الأخرى. المساعدات الثانية في تطوير خرائط لإمكانية زيادة أو نقصان "الضغوط" على التنوع البيولوجي وخدمات النظم الإيكولوجية من التطورات المحتملة في المستقبل، لدعم تنظيم السياسات في التخفيف من الضغوط التي تتعرض لها بعض المناطق ذات القيمة العالية.

ويبرز هذا الاستعراض أهمية الأخذ بعين الاعتبار ديناميكية من العوامل التي تؤثر على مدى ملاءمة الفيزيائية الحيوية من الأراضي للزراعة واحتمال الأراضي المستخدمة للإنتاج الزراعي. العامل الرئيسي الذي يؤثر الفيزيائية الحيوية ملاءمة الزراعية المستقبلية هو تغير المناخ. يستخدم النمذجة القائم على عملية لتقدير هذه التغيرات وآثارها. ومع ذلك، فإن مجموعة من العوامل السياقية أن 'قضية' أرض لاستخدامها بطريقة معينة أو لبعض المحاصيل هو ربما أكبر عقبة لكلا النهجين التي تستخدم النماذج التجريبية القائمة على العملية و.

وأخيرا، يوضح هذا التقرير أنه مع وصول أفضل إلى البيانات وتبادلها على نطاق أوسع من الطرق، كان هناك عدد متزايد من تقييم ملاءمة الزراعية؛ تطور مرحب به نظرا للضغط عالمي على الأرض للزراعة. الدراسات في هذا المعرض باستعراض هناك أيضا العديد من الطرق المبتكرة على المستويات الوطنية والمحلية المتعلقة بتنظيم استخدام الأراضي التي يمكن إدراجها في الدراسات العالمية والقارية. وسيكون التحدي للتوفيق بين عملية صنع القرار على مستويات متعددة، وتقلب من السائقين الاقتصاد الكلي من استخدام الأراضي، وتغييرات جوهرية في البيئة الفيزيائية الحيوية.

تم استعراض النهج نشرت باستخدام أسلوب مراجعة منهجية للأدبيات، يليه بحث في منشورات أكثر استهدافا للالنهج المستخدمة على نطاق واسع. تم تصنيف 136 الأوراق التالية المسائل الرئيسية المتعلقة بالهدف ومنهجية المراجعة. ويشكل هذا الاستعراض جزءا من مجموعة من الاستعراضات الفنية، بما في ذلك الاستعراضات على خدمات النظم الإيكولوجية ورسم خرائط التنوع البيولوجي، ووضع سيناريوهات ونماذج التغير في استخدام الأراضي، وهذه الوثائق يمكن استخدامها، جنبا إلى جنب مع أداة تقييم التنمية والقدرات، لدعم النهج القائم على النظام الإيكولوجي ل سياسات التنمية الزراعية وتخطيط استخدام الأراضي.

في تحليلنا، أعطيت الأولوية للدراسات التي وضعت أو استخدام تقديرات ملاءمة العالمية والقارية والإقليمية. ويولى اهتمام خاص لتقييم المقايضات المحتملة بين التنمية الزراعية (التوسع وتكثيف) على التنوع البيولوجي وخدمات النظم الإيكولوجية على المستويات العالمية والقارية، كما قدمت هذه الدراسات الطرق والدروس المطبقة على نطاق واسع.

أسفرت استعراض الأساليب المستخدمة في التقييمات العالمية والقارية مقياس من خمس النهج الرئيسية لرسم خرائط ملاءمة الزراعية:

النهج القائم على فسيولوجيا النبات:

1. توصيف الفيزيائية الحيوية من مناطق محددة مسبقا
2. النماذج التجريبية
3. نماذج مكانة بيئية
   - النماذج القائمة على العملية
   - نماذج محاكاة نمو المحاصيل المعتمدة على الموقع
   - نماذج النظم الايكولوجية الزراعية
   - نهج المناطق الزراعية الإيكولوجية -

النهج التي تنظر أيضا في المكونات الاجتماعية والاقتصادية للملاءمة:

4. توصيف الاجتماعي والاقتصادي والفيزياء الحيوية من مناطق محددة مسبقا
5. النماذج الاجتماعية والاقتصادية والفيزيائية الحيوية إلى جانب

الغالبية العظمى من الدراسات العالمية والقارية حول النهج القائم على عملية الاستخدام، ودمج المعرفة في فسيولوجيا النبات والاستجابات للضغوط غير الحيوية، ونهج منظمة الأغذية والزراعة للأمم المتحدة (FAO) الزراعية البيئية التقسيم (AEZ) هي الأكثر شيوعا من هذه. تؤثر القيود الاجتماعية والاقتصادية من احتمال أن استخدام الأراضي معين سوف يكون واجه في مكان معين وفي وقت معين، على الرغم من مدى ملاءمتها الفيزيائية الحيوية. من أجل تقييم احتمال الزراعة في أي مكان وزمان معين، وتقييم مدى ملاءمة الزراعية باستخدام منهجية AEZ تحتاج إلى أن تستكمل مع القيود الفيزيائية الحيوية والاجتماعية والاقتصادية أو مؤسسية إضافية و / أو الحوافز التي قد تؤثر على استخدام الأراضي المحتملين. النهج باستخدام المنطق الاستقرائي، مثل نماذج مكانة الايكولوجية، يستنتج ملاءمة الزراعية من أنماط الغطاء النباتي المكانية والزمانية الحالية. فهي مفيدة لتصور الصراعات المحتملة لاستخدام الأراضي وضمنا تأخذ في الاعتبار احتمال الزراعة، ولكن لا نعتبر العديد من العوامل الاجتماعية والاقتصادية التي من المعروف أن يؤثر ذلك على اختيارات استخدام الأراضي.

الدراسات التي تجمع بين النظم الزراعية الفعلية، ومدى ملاءمتها للمحاصيل متميزة، فإن العوامل المحلية التي تفضل محاصيل معينة أو استخدامات الأراضي وسيناريوهات الطلب العالمي وبالتالي تظهر لتقديم تقييم الأكثر اكتمالا من احتمال تحويل الأراضي إلى أنواع مختلفة من المحاصيل أو من غير الزراعي للزراعة أو لتكثيف الزراعة.

ويمكن حساب صلاحيتها للزراعة في أي مكان أو بكسل التي تتوفر بيانات (مثل العالمي التقسيم الزراعية الإيكولوجية؛ GAEZ).
الدراسات التي حددت مناطق أساسا فعلوا ذلك للمساعدة في تصميم البحوث المستقبلية أو كأداة اتصال. مناطق غالبا ما تخفي عدم تجانس العوامل المهمة لتحديد مدى ملاءمتها الزراعية واحتمال تحويل الأراضي أو تدهور الأراضي.

الدراسات العالمية والقارية في دقة عالية جدا (<5 km^2) لا تزال غير شائعة، ويرجع ذلك أساسا إلى عدم وجود بيانات المناخ مرتفعة للغاية الدقة أو بيانات عن خصائص التربة وظيفية. وتتعلق تدابير مشتركة من صلاحيتها لزراعة الكتلة الحيوية، أو العائد يمكن بلوغه، وكلاهما مخرجات مستوى المؤامرة. ومع ذلك عند تقييم مدى صلاحيتها للقرارات المتوسطة (5-50 km^2)، كل بكسل يمكن أن تمثل النظام الزراعي أو المناظر الطبيعية بدلا من محصول واحد، ولكن هناك حتى الآن أي تدابير ملائمة بأن تنظر مستويات نظام من هذا القبيل.

ملخص تنفيذي

يقدم هذا التقرير لمحة عامة عن النهج القائمة على رسم ملاءمة الزراعية، بما في ذلك استعراض البيانات الأساسية، على مختلف المستويات. خرائط استخدامات الأراضي ملاءمتها يمكن أن تساعد في تحديد أفضل الأماكن لمختلف استعمالات الأراضي المستقبلية ودعم استخدام أكثر كفاءة وفعالية للموارد والطاقة لتلبية الأنماط المتغيرة للاستهلاك البشري، إبطاء ظاهرة الاحتباس الحراري وتقليل معدل فقدان خدمات النظم الإيكولوجية والتنوع البيولوجي. ويسعى هذا الاستعراض إلى فهم أفضل المقاييس والجداول الزمنية المكانية التي كتبها النهج القائمة تعتبر الخريطة ملاءمة الزراعية والمعايير والأساليب المستخدمة لمدى ملاءمتها الحمير البرية للمحاصيل المختلفة أو أنواع استخدام الأراضي.

执行摘要

这份报告提供了现有的途径来映射农业的适宜性，包括基础数据进行审查，在不同尺度的概述。制图土地利用适宜性可以帮助识别不同的未来土地用途的最佳场所，并支持更有效地利用资源和能源，以满足人类消费，减缓全球变暖的变化规律，减少对生态系统服务和生物多样性丧失的速度。审查旨在更好地了解空间尺度和时间尺度由现行做法视为映射农业适宜性和用于评估土地适宜不同作物和土地利用类型的标准和方法。

发布时间方法被采用系统的文献回顾的方法，随后更有针对性的文献检索为广泛使用的方法审查。136篇论文进行了分类以下与审查的目的和方法的关键问题。这次审查形成了一套技术审查，包括对生态系统服务和生物多样性的映射，方案开发和土地利用变化模型评价的组成部分，这些文件可以使用，有能力发展评估工具一起，以支持基于生态系统的方法农业发展政策和土地利用总体规划。

在我们的分析，优先考虑的是研究，开发或使用的全局，大陆或区域适宜评估。特别注意的是在全球和大陆尺度评估对生物多样性和生态系统服务农业发展（扩张和集约化）之间潜在的权衡，因为这些研究提供了最广泛应用的方法和经验。

在全球和大陆尺度的评估采用的方法审查取得了五个主要的途径来映射农业适用性：

基于植物生理的方法：

1. 预先定义的区域生物物理学表征

2. 经验模型
   - 生态位模型

3. 基于流程的模型
   - 基于站点的作物生长模拟模型
   - 农业生态系统模型
   - 农业生态区办法

方法也考虑适宜的社会经济成分：

4. 预先定义的区域社会经济和生物物理特性

5. 加之社会经济和生物物理模型

绝大多数的全球和大陆研究审查使用基于流程的方法，结合对植物生理知识和应对非生物胁迫，联合国粮食和农业组织（FAO）农业生态区划（AEZ）的方法是最常见的这些。社会经济约束影响的特定的土地利用将在某一特定地点，并在特定的时间会遇到，尽管其生物物理适合性的可能性。为了评估在任何特定的时间和地点农业的可能性，使用AEZ方法适合农艺评估需要额外的生物物理，社会经济和制度约束和/或奖励，可能会影响潜在的土地使用加以补充。使用方法归纳推理，如生态位模型，推断农业适宜从现有的空间和时间的植被格局。他们是潜在的可视化土地使用冲突有用的，隐含考虑到农业的可能性，但不考虑许多已知会影响土地使用的选择社会经济因素。

结合了实际的耕作制度，适合不同作物的研究，有利于特定的农作物或土地用途和全球需求的情况下局部因素会因此出现提供土地转化的可能性最完整的评估，不同作物种类或来自非农业以农业或农业集约化。

适宜农业可以计算为哪些数据是可用的任何位置或像素（例如，在全球农业生态分区；GAEZ）。该定义的区域主要是研究这样做是为了帮助设计未来的研究或作为通信工具。区往往掩盖了对于确定适宜的农业和土地转换或土地退化的可能性的重要因素的异质性。

在非常高的分辨率（<5平方公里）的全球和大陆的研究仍然少见，主要是由于缺乏超高分辨率的气候数据或功能土壤特性数据。适宜的共同措施涉及植物生物量，或可达到的产量，这两者都是积电平输出。然而评估介质分辨率（5-50平方公里）的适用性时，每个像素可以代表一个耕作系统或风景，而不是一个单一作物，但也有尚未该考虑这样的系统水平没有适宜的措施。

有评估的土地用于农业的适宜性的两个重要目标。首先是提供可以用来计算潜在的农业生产信息，而第二个是确定土地转化的可能性，并从农业集约化或发生的可能性的基础上，适宜性和土地利用变化的驱动因素。首先将有助于（一）评价生物多样性和生态系统服务价值，并在方案中农业生产的地方适合，但是未使用区域被转化为农业之间的权衡或协同效应;（二）确定可能对生物多样性和生态系统服务价值较高的地区如果从当前不适于使用恢复，和（iii）确定本地和地区产量差距是农业效率的重要指标（实际产量和潜在产量之间的差）。这样的分析可以告知决策最有效地利用土地的农业用地和其他用地提供生态系统服务。在发展潜力日益地图或未来可能的发展减少对生物多样性和生态系统服务的“压力”的第二个辅助工具，以支持在减少对某些高价值区域的压力政策调控。

本文综述了考虑到了影响土地的农业和土地的可能性生物物理所适合用于农业生产要素的活力的重要性。影响未来农业的适宜性的主要因素生物物理是气候变化。基于流程的建模用于估计这些变化及其影响。然而，要以某种方式或某些作物被用于“原因”的土地环境因素的范围可能是对使用过程和基于实证模型两种方法的最大障碍。

最后，该报告显示，随着数据和更广泛地交流方法更好的访问，出现了农业的适宜性评估越来越多;一个可喜的发展给予的土地用于农业的全球压力。在本次审查节目的研究也有在与土地利用总体规划在国家和地方层面可能被纳入全球和大陆研究中的许多新方法。我们面临的挑战将是多层次的，土地使用的宏观经济驱动的波动，以及生物物理环境的根本变化调和决策。

1. Introduction

1.1 BACKGROUND AND OBJECTIVES

Over the coming decades, society will have to balance competing needs for land to feed a growing population, to provide resources and energy to satisfy the changing patterns of human consumption, to slow global warming and to reduce the rate of loss of ecosystem services and biodiversity.

Estimates suggest that some 446 million hectares of 'underutilised' land remain available for conversion (Deininger & Byerlee, 2010), mainly in Indonesia, Latin America (Argentina, Brazil, Bolivia, Colombia, Peru and Venezuela) and Sub-Saharan Africa (Angola, DRC, Mozambique, Tanzania, and Zambia). The extent and impacts of future land conversion to agriculture or other uses will depend on policy and other choices that society makes. For decision makers to balance different demands on land, it is crucial that they have access to spatial information on the suitability and the potential economic returns of land for alternative uses, the sustainability of these uses and their impacts on other resources. Land availability also plays an important role in that it may constrain the allocation of land for certain uses.

Economic or development planners can use the analysis and mapping of land use suitability and potential to identify the most suitable places for future land uses and support the allocation of production factors to sustainably meet the demands for food, feed, fuel and fibre of a growing population. Suitability maps and analyses can help answer questions such as how much land will be needed to meet these demands, where does this land exist and is conversion likely, where are shortages, what are the alternative uses of land, what are the main constraints to increased agricultural production, what are the potential impacts of conversion or agricultural intensification on biodiversity and ecosystem service values, and what will the likely impacts of climate change be?

The review was conducted in the first instance to support UNEP-WCMC's work under the 'Commodities and Biodiversity' project, funded by the John D. and Catherine T. MacArthur foundation. The report has since been revised and is being made available with a wider aim of building the capacity of national and sub-national decision makers to make informed choices using existing assessment results or developing a new assessment tailored to the question or region of interest. It forms part of a suite of technical reviews, including reviews on ecosystem services and biodiversity mapping, scenario development and land use change models, these documents can be used, along with a Capacity Development Assessment Tool (CDAT), to support an ecosystem-based approach to agricultural development policy and land use planning.

This report reviews existing approaches to mapping agricultural suitability at different scales, although focusing mainly on global, continental and regional scales. It does not seek to provide an analysis of all existing data on agricultural suitability, as too many criteria are involved and there is not one measure of suitability. Rather it seeks to provide an overview of existing approaches and their underlying data and criteria, so that - depending on the question, scale, and location of interest - an informed choice can be made to either develop a new tailored map of agricultural suitability or use the results of existing studies.

The review also considers whether studies sought to define zones for particular uses or use types, if suitability is based on the current agricultural system or on potential for different crops or land use types, and what factors they included in their assessments.

First, we consider and define some key concepts concerning agricultural suitability and potential. We follow this with a description of the methods used to review studies of agricultural suitability, and the results. Finally, we discuss in more detail the advantages and disadvantages of the main approaches and other considerations when choosing and using or modifying an assessment of agricultural suitability. We end with a set of recommendations for evaluating trade-offs or synergies between biodiversity and ecosystem services values and agricultural production and the likely future developments thereof.

1.2 DEFINITIONS AND IMPORTANT CONCEPTS

Net primary production

Terrestrial net primary production is the result of plants' ability to assimilate carbon dioxide and solar energy into biomass. Potential Net Primary Production can be calculated based on vegetation, precipitation and temperature (Del Grosso & Parton 2010). Agriculture is one of the greatest sources of the human appropriation of net primary production (Ewel 1999, Haberl *et al.* 2002), via the use of land and energy for the production of food, fuel and fibre (Vitousek *et al.* 1986).

Agriculture

Agriculture is the controlled use of land for the cultivation of other life forms - in particular crops and livestock - for the production of food, fibre, fuel, medicine and other products that support human well-being. Agriculture includes three main land uses: (i) arable (temporary crops, temporary meadows for mowing or pasture, market and kitchen gardens and fallow in which land is rested for less than five years), (ii) permanent cropping (long-term crops which do not have to be replanted for several years such as cocoa and coffee, and trees and shrubs producing flowers, and nurseries for 'non-forest' trees), and (iii) permanent meadows and pastures (herbaceous forage crops, either cultivated or growing wild for five years or more) (FAO 2014).

Land suitability

Land suitability traditionally addresses two questions: firstly, for any specified kind of land use, which areas of land are best suited? Secondly, for any given area of land, which kind of use is best suited? (FAO 1993). Some authors view capability as the inherent capacity of land to perform at a given level for a general use, and suitability as a statement of the adaptability of a given area for a specific kind of land use. Others see capability as a classification of land primarily in relation to degradation hazards, whilst some regard the terms "suitability" and "capability" as interchangeable (FAO 1993).

Land suitability for a particular use—the first question—can also have an economic (such as net present value or gross margins) or social components. This definition incorporates the costs of modifying or improving the land as well as the potential returns to the investment (Rossiter 1995). Another way of thinking about suitability is the likelihood of encountering a specific land use in a specific location (e.g. Heumann *et al.* 2012). A similar view is found in some land use modelling approaches that view suitability as the relationship between land use and its explanatory factors. These factors are not restricted to biophysical but may include dynamic economic or social determinants. Other definitions of land suitability make these distinctions more obvious and use the term "physical land suitability" (Alkimim *et al.* 2015), or "ecological land suitability" (Naughton *et al.* 2015) when referring to the biophysical capability or aptitude of the land.

For the purposes of this review, we define land suitability as the fitness of a given type of land for a defined use. Suitability is a judgement that considers the biophysical characteristics of a location, the economic feasibility of using the land for a specific purpose, and the sustainability of that land use. This assessment of suitability may or may not compare the suitability of alternative uses of the land.

Agricultural suitability

Agricultural suitability is a subset of land suitability and focuses on the first question posed by the Food and Agricultural Organization of the United Nations (FAO 1993), i.e. which are the areas of land best suited for agriculture? The agricultural suitability of any region, territory or otherwise delimited area of land depends on its intended use. Suitability also implies that the intended use is sustainable, i.e. that it does not result in degradation of the natural resource base or have negative social impacts.

Measuring and mapping agricultural suitability

Mapping agricultural suitability requires attributing a suitability rating to defined areas of land (or "Land Units") based on the combination of the requirements for the intended agricultural use with the characteristics of the land. A land unit (LU) is therefore considered uniform in view of the requirements of its intended use, where local variation does not affect the performance of the land for that use (Driessen & Konijn 1992).

The suitability of a given area for crop production can be assessed in many ways, from rules of thumb based on a single factor such as rainfall to complex models that simulate crop growth under many climate, soil, plant, and management variables (You *et al.* 2014). Studies can use quantitative approaches such as scoring systems or qualitative approaches to rate suitability, e.g. a description or ordered classification in relation to soils: good, moderate, bad, serious. Other social and economic factors that affect the feasibility or sustainability can also be combined with the biophysical aptitude depending on the purpose of the suitability assessment.

Yield is an important concept because studies of suitability for a particular crop or animal can use it as an objective measure of suitability and which can be converted into calories, protein and money (Grau *et al.* 2013).

Crop yield

Crop yield can be measured for any part of the plant that is destined for use, such as the leaves, roots or fruits. Potential yield is the yield that a certain crop could achieve based on the prevailing solar radiation and temperature, without any constraints concerning water, nutrients and reducing factors such as pests and diseases. We define potential yield (Yp) for different systems as "the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled (Evans 1993, Van Ittersum & Rabbinge 1997; Van Itterseum *et al.* 2013). Therefore, solar radiation, temperature, CO_2 concentration, and genetic characteristics define crop growth. Potential yield is location specific because of the climate, but in theory not dependent on soil characteristics" (http://www.yieldgap.org/glossary).

In large parts of the world, agriculture is rainfall dependent and therefore limited by seasonal rainfall patterns in terms of timing and quantities. "For rainfed crops, water-limited yield (Yw) is the most relevant benchmark. Yw is defined similar to Yp, but crop growth is also limited by water supply, and hence influenced by soil type and field topography" (http://www.yieldgap.org/glossary). The calculation of potential and water-limited yields assume that soil nutrients are adequately managed as part of the crop management, however this is not always the case so these yields can also be further limited by a lack of nutrients (Figure 1).

Water and nutrient limited yield does not take into consideration the impacts of reducing factors such as pests and diseases, but in practice these affect yields in most production systems and places in the world.

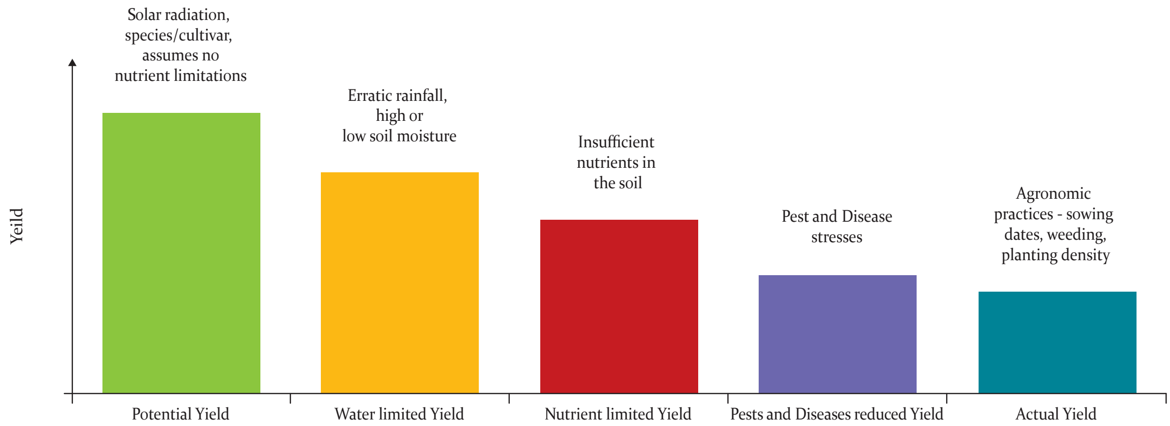

Figure 1: Factors contributing to gaps between actual and potential crop yields

The actual yield is the yield generally achieved by farmers in a given area under existing land characteristics (climate, soil and biophysical characteristics) and the dominant land and crop management practices. The yield gap is the difference between the potential and actual yield. The yield gap is important because it shows how important management is in attaining yields closer to their potential and this has impacts on the amount of land required, i.e. the bigger the gap, the more land is needed to attain the same amount of production as under the potential yield. It can also be used to identify areas where crop yields are low compared to crops in the same or a comparable region and hence can act as a tool for targeting agricultural improvements.

Resource use / ecological efficiency

Difficulties with using yield as the (only) measure of suitability can occur when more than one crop is being considered, such as in the measurement of the productivity of a whole farm or landscape. Over larger areas yield from an optimal mixture and allocation of crops can be aggregated to give an indication of the potential biomass production increase (PBPI) – which is roughly equivalent to the yield gap (Mauser *et al.* 2015). There may also be other factors associated with agricultural production that contribute to the sustainability of production and to other environmental services (which are also beneficial to agriculture) but which may appear to be sub-optimal in terms of yield or value. Examples include inter-cropping, rotations, or use of break crops, which contribute to more sustainable agriculture by e.g. increasing resilience, natural pest control and soil fertility, but often lead to lower per hectare outputs (Rusinamhodzi *et al.* 2012, Hauggaard-Nielsen *et al.* 2008, Ratnadass *et al.* 2012).

Resource use efficiency, in contrast to the yield gap, considers all the output as a proportion of the inputs (van Noordwijk & Brussaard, 2014), which also include the externalities associated with chemical fertilisers and pesticides. Closing the yield gap at the expense of an efficiency gap is unlikely to lead to a sustainable agricultural system.

Land characteristics

Land is characterised by climate, soil and other biophysical characteristics that determine the supply of water, energy and nutrients to plants. Land characteristics can be single or compound. Single land characteristics can often be expressed as a number, such as average annual rainfall, slope, and soil depth. Compound land characteristics are a function of combined single characteristics, such as available water capacity (water in the soil available to plants) which is a function of soil depth, organic matter content and physical properties of the soil (Driessen & Konijn 1992). Different combinations and interactions of single and compound characteristics affect the suitability of land for different crops and the yields that may be achieved. Different land characteristics can be weighted to give an aggregate characteristic that determines land suitability largely independently of other land characteristics or combinations thereof. For example, water availability to a crop is dependent on rainfall and potential evapotranspiration, in combination with available water capacity, as well as on the interactions between them (Driessen & Konijn 1992).

Land units can also be characterised by the socioeconomic factors affecting suitability for a particular use of land. Those factors—such as availability of labour, or access to markets—may not be inherent to the land and are dynamic like climatic factors and their contribution to suitability depends on the use being considered.

2. Methods

We reviewed published approaches to mapping the suitability and potential of land for agriculture, up to February 2015, using a systematic literature review followed by a more targeted literature search for widely used approaches. A list of search terms used can be found in Appendix 1.

2.1 SELECTION OF PAPERS FOR REVIEW

A largely subjective positive screening approach was taken, which started by selecting papers based on the research area or discipline of the source e.g. agricultural, environmental or earth sciences. We followed with selection based on methodological development (i.e. concentrating on papers that develop zones or other assessments of suitability), on spatial extent (at least national but recognising that local studies provide insights on non-biophysical factors), as well as the potential of papers to reference other sources that describe agro-ecological zoning (AEZ) or assessments of suitability (see Appendix 1). We subsequently expanded our selection by snowball sampling from citations in key texts. The selection process resulted in a list of 136 papers.

We classified each study using the titles and abstracts of the literature. Our classes related to key questions around the purpose and methodology of this review (see Table 1 for a list of key questions and their rationale).

We made the decision to prioritise studies that developed or used suitability assessments at the global level or for specific continents or groups of countries. These studies were prioritised as trade-offs between agricultural development (expansion and intensification) and biodiversity at the global and regional scale provide the most widely applicable methods and lessons. The spatial extent of the study will often determine the methods and data that are used to assess suitability for agriculture, the spatial resolution of the input data and results, and the choice of factors that are considered in the assessment. The results of this review will therefore be biased towards agricultural mapping at global and continental levels and towards the search terms used in the review e.g. AEZ studies.

Table 1. Themes for coding and their rationale

Key question	Rationale	Values
Year of publication?	To track the evolution of agricultural suitability assessments over time.	Year
Spatial Extent?	To show the spatial applicability of the approach, and for analysing relationships between extent, resolution and the basis of suitability and the data available.	Global Continental / multi-country National Local
What method does the assessment use to measure suitability for agriculture?	To understand the number and nature of possible approaches to measure suitability and which is most appropriate in which situations.	
Spatial Resolution?	To show the potential trade-offs between accuracy, precision, data quality, usefulness, and applicability.	Low Resolution (> 30' or 50km²) Medium Resolution (2.5'-30' or 5-50km²) High Resolution (< 30' or 5km²) Site specific No information or mix of resolutions
Does the study seek to assess the suitability/potential of a particular crop/ animal or agriculture in general?	We hypothesise that studies focusing on a single crop use different methods to those focusing on agriculture in general. We might also expect differences in the 'accuracy' or the 'performance' of the method depending on the generality or specificity of the assessment.	Specific crops Agriculture Other
What is the biophysical basis for the assessment of suitability?	Biophysical factors, which in combination define the potential and actual yield of a crop or of a cropping or livestock system, are the primary determinants of agricultural suitability. Climatic factors, along with latitude, define the potential yield of a crop. Soil factors will limit the yield of a crop if nutrients are deficient, if there is an excess of other elements, if the structure impedes growth or if soil fauna are not balanced. Pests and diseases are yield-reducing factors. Terrain can also reduce yield by hindering management or promoting land degradation.	Climatic factors Soil factors Pests and diseases Terrain factors Other biophysical factors
Do studies incorporate factors that are not biophysical in their assessments of agricultural suitability?	Does the study consider non-biophysical factors that affect the yield gap of a particular crop such as access to inputs, crop protection and management practices? In addition, does the study consider non-biophysical factors that affect the likelihood of a particular crop or system in a particular location, such as labour, land tenure, culture, and access to markets?	Access to markets Land Tenure/land quality/ land availability Culture Other

Theme	Rationale	Values
Does the study seek to define zones?	The end-result of an assessment is important for the applicability and usefulness of a study. For instance, zones might be useful for general situational analysis of planning. Whereas a more continuous surface might be used in combination with other data or to produce a numerical evaluation (e.g. comparing actual yield with potential yield).	
If zones are defined are they based on the current agricultural system or the potential for different crops/systems?	To assess whether the study takes into account dynamism in the factors that determine suitability (and likelihood).	Current agricultural system Potential for different crops Other
Reference time period?	This is an important consideration in the context of climate change, changes in demand, and for validation of assessments.	pre 1960 1960-1990 1990-2015 2015-2100
Organisation(s) that carried out the study?	To determine the range of organisations that use and produce assessments of agricultural suitability.	

3. Results

3.1 MAIN APPROACHES

The review highlighted five main approaches to mapping agricultural suitability.

Approaches based on plant physiology:

1. Biophysical characterisation of pre-defined zones
2. Empirical models
   - Ecological niche models
3. Process-based models
   - Site-based crop growth simulation models
   - Agro-ecosystem models
   - Agro-Ecological Zones approach

Approaches that also consider socioeconomic components of suitability:

4. Socioeconomic and biophysical characterisation of pre-defined zones
5. Coupled socioeconomic and biophysical models

The most common approaches incorporate processes of plant physiology and responses to abiotic stresses. The FAO AEZ method is the most commonly used approach and has been used for continental scale assessments but seems to be especially well suited to global studies. However, we encountered many other studies that concentrate on plant physiology and yield response to the environment, especially for studies conducted at the continental scale that use alternative methods (Figure 2). The biophysical characterisation of existing zones is relatively more common for continental scale assessments (e.g. Devendra & Thomas 2002); in this class we also include initiatives to improve baseline data on actual global extent and intensity of agriculture (e.g. Ramankutty & Foley 1998, Monfreda *et al*. 2008). Methods that couple biophysical and socioeconomic factors to assess suitability or characterise regions are less common than purely biophysical models, however they are becoming more popular, with all except one study carried out since 2000. Studies using empirical models to generalise on the suitability for agriculture based on current distributions were not widely used to assess the suitability for agriculture in general; ecological niche models were a notable subset of these approaches.

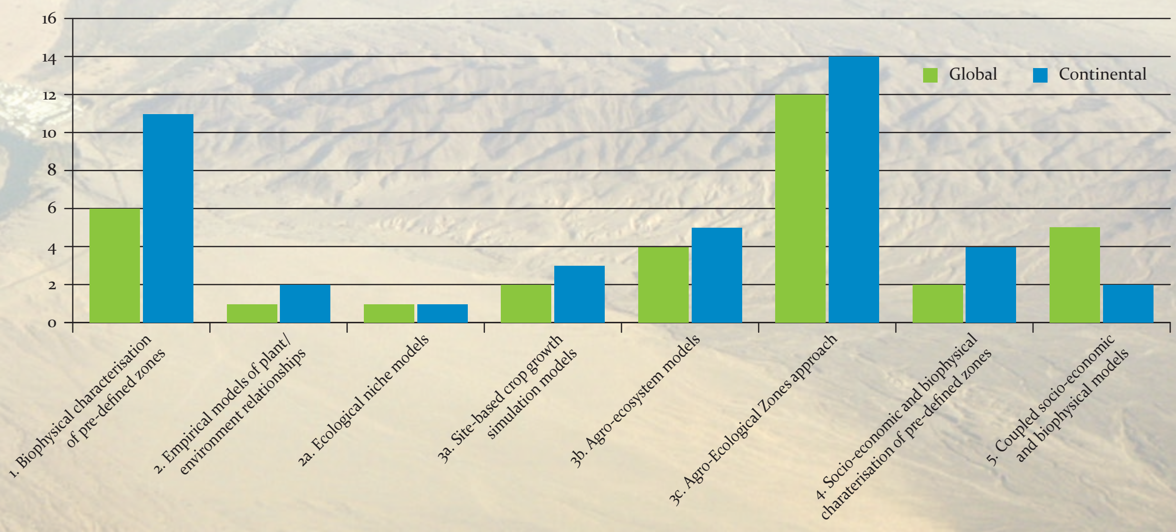

Figure 2: Number of global and continental level studies per approach

We review in detail each of the main approaches of those studies that have a continental or global extent. Table 3 at the end of Section 3.1 presents an overview of the pros, cons and recommended situations of use of each approach for comparison.

Approaches based on plant physiology

Approaches based on plant physiology evaluate the suitability of a land unit for agriculture or a particular crop on the analysis of a combination of biophysical factors in relation to the requirements of that system or crop. Temperature is often the first determining factor as it drives plant growth (Ramankutty *et al.* 2002b). Far fewer studies consider solar radiation, despite its importance for defining yield potential, in contrast to water availability, which is the major yield-limiting factor. Many studies further modify the climatic suitability using soil, and terrain characteristics.

Biophysical characterisation of pre-defined zones

A large group of the studies in our review did not seek to evaluate suitability, but instead to characterise pre-existing AEZ or regions often for the purpose of targeting or recommending interventions that would improve agricultural productivity or contribute to a social objective like reducing poverty.

Examples, such as De Pauw *et al.* (2000), seek to improve the spatial resolution of existing zones so as to identify agro-ecological niches that support higher agricultural productivity, which allow better targeting of agricultural development interventions. Other studies provide a baseline for future research improving or updating information on commonly reared livestock (e.g. Devendra & Thomas 2002, Seré *et al.* 1995) or dominant cropping systems (e.g. Monfreda *et al.* 2008, Ramankutty & Foley 1998).

Empirical models

A small proportion of the approaches were based on models that empirically relate factors affecting plant physiology with indicators of suitability for agriculture. A good example of this type of model is a global assessment of agricultural suitability based on an examination of the relationship between cultivated land, climate variables and soil characteristics/constraints (Ramankutty *et al.* 2002a). The authors fit probability density functions to a limited set of drivers – growing degree-days, moisture index, soil carbon density and soil pH – and map these globally. They then assess the sensitivity of the suitable areas to changes in temperature and rainfall and assess the impact according to climate change scenarios. Wortmann *et al.* (1998) construct suitability environments for common beans, also based on a combination of factors associated with plant physiology. These factors are elevation (as a proxy for temperature), annual rainfall, day length and soil acidity, each of which has an effect on plant growth. The purpose of constructing different bean environments was as to provide information for targeting bean varieties that are well adapted to the factors in those environments.

Hawkins *et al.* (2003) do not look at suitability *per se* but instead relate environmental factors like temperature and rainfall with species richness. They show that the importance of different variables changes spatially, with energy a major determinant in high latitudes and water variables the strongest predictors of species richness in warm temperate, sub-tropical and tropical zones.

Many geographic land use models (e.g. CLUE; Verburg & Overmars 2009) incorporate empirical models of land use suitability based on a statistical examination of current land use and hypothesised drivers.

Ecological niche models

In this class we include two older studies that used observations of vegetation as an index of agricultural potential. The more recent publications that we reviewed used maximum entropy ecological niche models to predict the presence of different kinds of land use (cropping, sedentary animal husbandry, pastoral systems and hunter-gathering) based only on climatic and soil properties (Beck & Sieber 2010), and used the relationships to investigate the potential impacts of climate change (Beck 2013). The authors suggest that a benefit of their method is the simple model that considers agriculture as a whole; however, the 2013 paper does not consider palm oil, which is a major driver of land conversion in the humid tropics.

These models are particularly useful for visualising potential land use conflicts and implicitly take into consideration the likelihood of agriculture (because they are based on the existing presence) but deliberately do not consider many of the socioeconomic factors that are known to affect land use choices. Ecological niche models that focus on specific crops and which consider a wider range of variables might therefore provide alternative or complementary results to the AEZ approach. Beck and Sieber (2010) actually consider the validation of their model and compare with FAO land cover, albeit with few classes and consider their results as a second opinion.

Process-based models

The most common approaches were models of suitability based on the processes and the biophysical factors affecting crop growth. We follow the Rosenzweig *et al.* (2014) classification of these models in three types: (i) site-based crop growth simulation models, (ii) agro-ecosystem models, and (iii) agro-ecological zone models. Each of these type of models differ in their assumptions, processes and their structures.

Site-based crop growth simulation models

A small number of the studies used crop growth simulation models over large areas to assess the suitability of one or more crop. These models simulate the growth of a crop species or variety over the whole growing period for a specified location with information about the soils and day length. Different models have different time steps (e.g. hourly, daily, weekly) that have consequences for the weather information required and the kind of crop management that can be simulated. These models can be run for multiple locations and the results used to assess suitability, especially when simulations are run for multiple cropping seasons.

Examples of these models in our literature search date mainly from the 1990's and include Groot *et al.* (1998) who model wheat, rice (as proxies for rainfed cropping and irrigated cropping) and grassland which is assumed to be fed to livestock. The authors convert the results of the models into grain equivalents and apply two growth scenarios – yield oriented and environment oriented agriculture – and summarise for 15 world regions. Van Keulen and Stol in contrast concentrate on a specific crop (potato) and compare the suitability in different zones in Latin America, Africa and Asia. A common aspect of many of these models was to define zones based on an analysis of meteorological data with representative meteorological stations (e.g. van Lanen *et al*. 1992) rather than model for smaller individual grid cells. Both van Lanen *et al*. (1992) and Carter *et al.* (1991) model crop potential in Europe at a time when the environmental impacts of intensive agriculture were being debated.

Agro-ecosystem models

These models are similar to crop growth simulation models but are designed for modelling larger areas. They mainly simulate nutrient and water cycles over time and relate these cycles to primary productivity. These models are computationally less complex than site based models and have a long history in the literature. Kellog and Ordeval in 1969 were using these models to assess the potentially arable soils of the world. De Pauw (1982) used a water balance approach to assess key determinants of the growing period for crops, which is a key component of crop productivity. The methodology developed in this paper was subsequently used in national studies of suitability for rainfed agriculture (e.g. de Pauw 1983).

More recent assessments, such as Cassel-Gintz *et al.* (1997), combine various factors affecting the marginality of agriculture using fuzzy logic. They apply a simple photosynthesis model to simulate crop growth as part of an index of unfavourable growth conditions. This is subsequently combined with slope to produce a global index of marginality that can be used to identify constraints to agriculture as well as to compare with actual cropping patterns as a guide on potential areas of environmental degradation. Imhoff *et al.* (2004) use a vegetation index combined with historical climate data to calculate net primary productivity. The authors show where net primary productivity is being appropriated by humans and are able to show the footprint of human consumption.

Agro-ecological zone models

The most common methodology is the Agro-Ecological Zoning (AEZ) approach developed by FAO in collaboration with IIASA to provide a "standardized framework for the characterization of climate, soil, and terrain conditions relevant to agricultural production". It is "a GIS-based modelling framework that combines land evaluation methods with socioeconomic and multi-criteria analysis to evaluate spatial and dynamic aspects of agriculture" (Fischer *et al.* 2002; p4). The increased availability and quality of global databases of climate, soil, terrain and land cover have enabled a continuous improvement of AEZ calculation procedures. The Global Agro-Ecological Zoning (GAEZ) assessment of land suitability led to a database of global spatial land resources that support the assessment of the suitability, biophysical limitations and production potential of major food and fibre crops, under various levels of inputs (Fischer *et al.* 2002, Van Velthuizen *et al.* 1995). The agronomic suitability assessments using the AEZ methodology can be complemented with additional biophysical, socioeconomic or institutional constraints that may affect potential land use, such as e.g. built-up areas, barren land, forests, protected areas, irrigation areas, or population, to suit multiple assessment objectives (Fischer *et al.* 2002). FAO and IIASA released the latest version (3.0) of GAEZ database and data portal in May 2012.

The approach was developed at a global scale but has been used also to map agricultural suitability at regional (Higgins & Kassam 1981, Sys 1993, Verheye 1986) or national scales. The spatial resolution of the GAEZ is five arc minutes or approximately 9 × 9 km at the equator.

The GAEZ presents the agro-ecological suitability and productivity for 280 ideotypes of 49 crop species for four input levels (high, intermediate, low and mixed). The 'high' level assumes the best farming technology, soil nutrient inputs, and management at the time of the assessment. GAEZ also calculates suitability and productivity for five water supply system types (rain-fed, rain-fed with water conservation, gravity irrigation, sprinkler irrigation and drip irrigation). These are available for a baseline climate (1961-1990) and for projected future climate conditions.

Crop suitability per grid cell in the AEZ approach is a result of a combination of the following:

1. Agro-climatic crop suitability assessment (enabling calculations of biomass, potential yields, water-limited potential yields, crop water requirements and deficits).
2. Agro-edaphic suitability assessment, where requirements of crops/LUTs are compared with prevailing soil and terrain conditions, including constraints e.g. landform.
3. Terrain-slope suitability assessment, based on the workability and accessibility of land as well as considering potential levels of erosion and fertility loss.

For the agro-climatic suitability assessment, the following steps are taken from (Fischer *et al.* 2002):

1. A grid-cell-specific agro-climatic characterisation, including calculation of thermal climates, temperature profiles, and temperature and moisture growing period characteristics (most AEZ studies use reference growing periods).
2. Calculation of temperature and radiation limited potential crop yields, quantification of moisture-stress-related yield limitations, and determination of optimal crop calendars.
3. Application of limiting factors to account for yield-limiting agro-climatic constraints, providing the attainable crop yields.

FAO and IIASA establish soil characteristics related to crop yield from the basic requirements of crops. "For most crops and cultivars, optimal, sub-optimal, marginal and unsuitable levels of these soil characteristics are known and have been quantified. Soil suitability classifications are based on knowledge of crop requirements, of prevailing soil conditions, and of applied soil management. In other words, soil suitability procedures quantify to what extent soil conditions match crop requirements under defined input and management circumstances" (FAO 2015).

The results are classified into five basic suitability classes according to the proportion of the maximum potential crop yields that can be attained (Table 2).

Table 2: Suitability classes (adapted from Fischer *et al.* 2002)

Suitability class	Percentage of potential yield
Very suitable (VS)	80–100
Suitable (S)	60–80
Moderately suitable (MS)	40–60
Marginally suitable (mS)	20–40
Not suitable (NS)	0–20

Approaches based on socioeconomic and biophysical factors

Suitability of agriculture depends not just on the aptitude of the land to support agriculture but also the value placed by society on agricultural products vis-a-vis other ecosystem services, as well as the feasibility of exploiting natural resources for agriculture.

Many approaches have attempted to incorporate both biophysical and socioeconomic factors, by either (i) characterising existing zones, or (ii) explicitly incorporating socioeconomic factors in models of suitability.

Socioeconomic and biophysical characterisation of pre-defined zones

The earliest example of these approaches in our sample was descriptive (Beets 1978), with an assessment of the factors that affect the aptitude of the land for agriculture as well as the management and the links to consumption via self-sufficiency. In an evaluation of national data Fulginiti *et al.* (2004) calculated agricultural productivity growth and sought to explain trends over time using national institutional and socio-political factors. This does not show the suitability of land for agriculture but can provide some insights into the likelihood for intensification (closing the yield gap) as opposed to conversion of non-agricultural lands in the face of rising demand for agricultural products. The implications for mapping suitability would be that purely socioeconomic factors at the national scale could place limits on the likelihood of agricultural intensification or conversion at more local scales. More spatially precise datasets of agricultural intensity were compared with population for different time periods (Ramankutty *et al.* 2002b). These data can inform land use models and subsequently can be used to infer the processes that drive land use conversion and agricultural intensification. The results show how different 'fertile frontiers' have been exploited over the past century but the authors conclude that there are no more frontiers left to exploit, implying further intensification of existing croplands or expansion into 'marginal' areas.

Other characterisation of zones combined different data to produce a composite index. The major differences between the approaches are the methods used to combine the factors. Studies such as Awulachew *et al.* (2010) and Pender *et al.* (2006) sought to combine disparate data sources to identify relatively homogeneous zones or 'domains' that could guide agricultural and other interventions in a wider region. These approaches defined thresholds for key factors and combined the resulting classes in a Boolean manner. In contrast to Boolean combinations of a small number of factors, Václavík *et al.* (2013) combined multiple land use, environmental and socioeconomic factors using a form of artificial neural network to define a small number of global land system archetypes. This method avoids subjective choices of the most important indicators and thresholds, instead creating zones that reduce variability in multi-dimensional space.

Coupled socioeconomic and biophysical models

Assessments that consider socioeconomic constraints to suitability share commonalities with studies of the adoption of agricultural technologies. In the former case, there are certain factors that will affect the likelihood of a particular land use, whereas in the latter those factors will affect the likelihood of a farmer, community, or region using a specific technology. The consideration of these factors marks the difference between 'modelling to compare suitability' and the likelihood that a particular land use will be encountered at a particular time. In some cases the strength of a socioeconomic constraint or driver of demand may lead to conversion of land to agriculture even in areas of marginal suitability (Abram *et al*. 2014).

The coupled models that we reviewed do not consider the demand for land in isolation, unlike other purely economic models (e.g. Hertel 1997), and incorporate information on the biophysical suitability for agriculture in general or for specific crops. The assessments in this class are oriented more towards the likelihood of conversion given certain suitability constraints.

An early methodological study (Christiansen 1979) recommended the calculation of carrying capacity and potential crop productivity. Carrying capacity was a useful term to assess which areas would be able to support different populations – and therefore, in the context of suitability, would allow for the identification of areas which would be able to sustain more people, and which might be converted to agriculture or experience intensification, or areas already above their theoretical carrying capacity which might suffer degradation or food insecurity. Social processes were included in the CGIAR Technical Advisory Committee report on marginal lands (2000). The report defines different levels of suitability of land for agriculture, which depend on the severity of biophysical and socioeconomic constraints. For instance marginal agricultural lands are those which have limitations that make sustainable agricultural use difficult, and are characterised by soil and/or climatic constraints, and/or absence of markets, poor infrastructure or restrictive land tenure. This approach is put into wider practice by Lambin *et al.* (2013) who consider alternative uses of land to agriculture, and also recognise that non-agricultural land is not unused but rather underutilised, and that an increase in utilisation, or conversion to agriculture has social and environmental impacts. In their attempt to calculate land available for agriculture the authors exclude mature forests and protected areas from land that could be converted. They then exclude areas where the impacts on ecosystems or social services would be greater than the benefits of conversion to agriculture. The authors calculate costs based on the different constraints to conversion or intensification and the measures required to overcome those constraints – these measures include building infrastructure, or improving institutions. They also consider the trade-offs associated with those measures such as environmental degradation or migration.

Finally, there are approaches that couple biophysical and socioeconomic systems in a dynamic manner. A good example is Fischer *et al.* (2005) who used the GAEZ method in combination with the results of global circulation models with four socioeconomic emissions scenarios to assess potential changes in crop yield. They incorporated these potential climate change impacts in an economic analysis and assessed how the interaction with trade and food demand would affect food production and food security. The study modelled changes in agricultural suitability using the AEZ approach, but in addition couples these projections with demand scenarios which altered the likelihood of agricultural expansion or intensification. A more recent study (Mauser *et al*. 2015) coupled a crop growth simulation model for a larger number of crops. They went further than previous studies and allocated mixtures of these crops optimising for yield or for profit. The result of the coupled model was an assessment of the change in potential biomass production over current production. The model simulated production potentials given current cropping intensities, then modelled the additional potential of cropping intensity and finally considered the reallocation of crops spatially and temporally to optimise profit.

Studies that combine actual cropping systems, suitability for distinct crops, local factors that favour particular crops (Lambin *et al.* 2013) or land uses and scenarios of global demand would appear to offer the most complete assessment of the likelihood of conversion of land to different crops or from non-agriculture to agriculture (Mauser *et al.* 2015).

Table 3. An overview of the pros, cons and recommended situations in which to use each approach to mapping agricultural suitability.

Approach	Pros	Cons	Recommended situations
Biophysical characterisation of pre-defined zones			
Biophysical characterisation	Can potentially be easily validated	Requires further calculations or modelling to assess suitability	Providing baseline and targeting data for future research
Empirical models			
Empirical models	Can consider multiple crops/land uses	Assume explanatory factors are stable over space and time	For modelling suitability of specific crops where explanatory factors are stable over space and time
Ecological niche models	Based on actual distribution of crop/agriculture	Require absence and presence data Explanatory variables chosen may not include important factors that determine presence	
Process-based models			
Site based crop-growth simulation models	Provide an accurate assessment of crop performance and risk Can simulate novel environments	Require a lot of data to calibrate and run the model Computationally intensive	Should be used where data and computational infrastructure allow
Agro-ecosystem models	Less complex than site-based models Allow regional adaptations in farming practices	Often lack crop and management detail	For modelling large areas where calibration data for site based crop growth models are unavailable
Agro-ecological zones approach	Combines components of both site based and agro-ecosystem models Has a well-developed database	Does not consider competition from other land uses or performance other than yield	As an input into coupled biophysical and socioeconomic models

Approach	Pros	Cons	Recommended situations
Socioeconomic and biophysical characterisation	Can potentially be easily validated Can incorporate multiple dimensions of agricultural suitability	Requires further calculations or modelling to assess suitability	Providing baseline and targeting data for future research
Coupled socioeconomic and biophysical models	Incorporates both the aptitude for agriculture and the likelihood of that land use Can take into account costs of intensification and conversion Can optimise for different land use objectives	Potentially computationally intensive	

3.2 SUITABILITY OF CROP OR GENERAL AGRICULTURE

The purpose of the agricultural suitability assessment may focus on a particular crop or animal species or on the suitability of agriculture in general (Figure 3). An increasing number of studies focus on individual crops, however there have also been more studies concentrating on agriculture as a whole, especially since the 1990's (Figure 4).

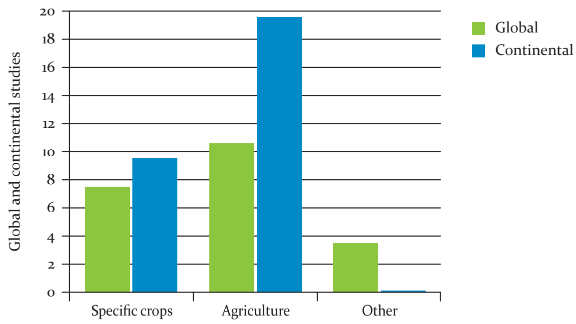

Figure 3: Number of global and continental level studies per focus topic

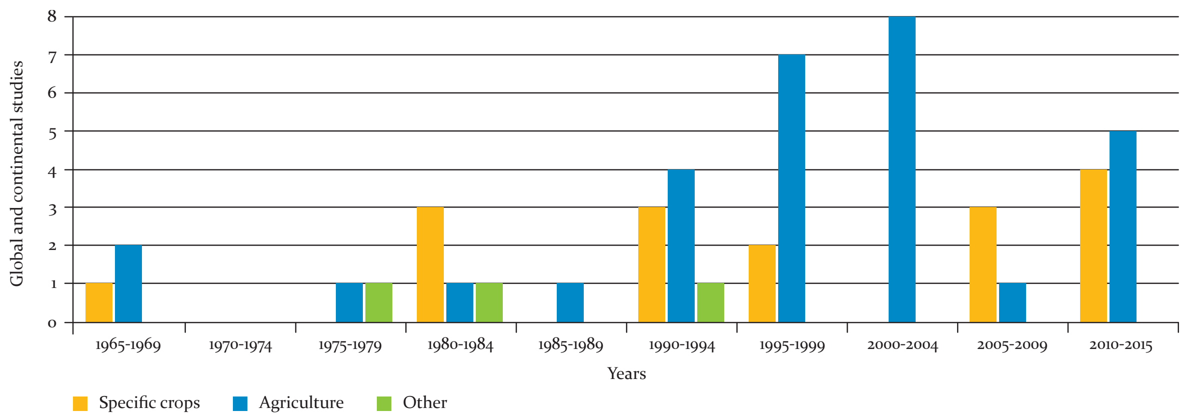

Figure 4: Number of global and continental level studies in 5 year periods per focus topic

Many of the studies that look at a particular crop take advantage of the GAEZ database which provides information on 49 different crops. Studies that concentrate on the suitability of specific crops used a variety of methods ranging from mechanistic models such as EcoCrop (e.g. Ramirez-Villegas *et al*. 2013; Läderach *et al*. 2013) to more dynamic site based crop growth simulation models. Assessments of specific crops will be useful when considering a crop that has a growing demand (such as soybean, sugarcane or oil palm), or which has been shown to be suitable in areas which also provide other important ecosystem services. The theoretical suitability of individual crops is easier to assess than a combination of crops within an individual 'farm system' (Giller 2013) or over larger areas when the combination of farms is classified as agriculture. van Wijk *et al*. (2009) have shown that improving the modelling of interactions between crops and with livestock are more important for gauging whole farm productivity than modifying individual crop models – suggesting that assessments of agricultural suitability should not focus only on the yield of crops in isolation but as total farm productivity. Farm systems can be designed according to various objectives such as meeting the food requirements of the farm household, maximising the income from selling agricultural products (Waithaka *et al.* 2006; Mauser *et al*. 2015) or increasing resilience (Tittonell 2014).

Three constraints determine the presence of a particular species (Soberón & Peterson 2005, Soberon, 2007), firstly the local environment allows the species to grow (Grinnellian niche), secondly the interaction with other species allows the species to persist (Eltonian niche), and thirdly that the location is accessible. In the case of wild species of plants and animals the second and third constraints will be determined by the competitiveness, and the dispersal abilities or mechanisms of the species, but for agriculture these capabilities are modified in great part by human agency (Ojiem *et al*. 2006). You *et al*. (2014) use a price function to weigh the likelihood of a particular crop in a particular location while Fischer *et al*. (2002; pg 91) suggest six different weights which can be applied to yields to compare cereals: Unit value ($/ton), Calorie content (kcal/100g), Protein content (g/kg), Food conversion rate (%), Food energy weight and Nutritive weight. These weights address the second niche constraint but would need to be expanded to consider the competition between 'agriculture' and other land uses or livelihood strategies. At a local scale Heumann *et al*. (2012) define the three niche constraints for modelling the suitability for agriculture. They consider the socio-environmental niche for a particular crop to be a set of environmental and social conditions that provide a yield and income to households. However they use proxies for some of the socioeconomic conditions and see different response curves for different crops. The variables chosen (both socioeconomic and environmental) were locally relevant and are unlikely to be useful at the global or continental scales but the method is promising and attempts to introduce human agency to a species distribution model.

There is a greater diversity of methods for the assessments that consider the suitability for agriculture in general, but there are two broad approaches. The first is to take into account a variety of different crops and then compare or sum the suitability of each. Groot *et al.* (1998) consider three crops (rice, wheat and grassland) as proxies for irrigated, rain fed and feed crops respectively. They allocate land and water within catchments to the most productive types of agriculture first and then calculate total production for a particular grid cell based on its proportion of irrigated crops, rain fed crops and grassland. Meanwhile Zabel *et al*. (2014) calculate fuzzy membership functions based on the physiology of sixteen food, feed and energy crops. They compute the suitability for each crop for each pixel and the highest value between the different crops is chosen as the suitability for agriculture. An even more ambitious approach has been taken by Mauser *et al*. (2015) who model the potential biomass of eighteen crops and compare with actual yields, optimum cropping intensities of current crop mixtures, as well as profit-maximising allocation of crops. Koning and van Ittersum (2009) also show the progression in complexity of farming systems from long fallow through zero-fallow to green revolution production systems, charting the increases in energy inputs, and the resulting increases in outputs. These comparisons allow for inferences on the effect of management on the land required to feed the global population. The GAEZ approach has also been used to assess land with potential for cultivation by the cumulative addition of the area classed as suitable for each crop with different levels of suitability selected for different levels of input (Fischer *et al.* 2002). However, Seo (2014) evaluate the GAEZ approach with actual farmers' decisions in the context of a changing climate, and conclude that decisions on substitution or changes in practices might not be well predicted using the GAEZ approach.

The second approach considers agriculture to be a specific land use type. Cassel-Gintz *et al.* (1997) use a similar fuzzy membership method to Zabel *et al.* (2014) but adopt a decision-tree approach to consider some general parameters for the marginality of agriculture dependent on climate, soil and terrain, i.e. the inverse of suitability. Beck and Sieber (2010), in contrast, use ecological niche models to assess the suitability of agriculture as a livelihood strategy along with hunter-gatherer, pastoral or sedentary animal production. They produce an index of shared suitability based on climate and soil which denotes potential conflict areas where different types of strategies (and land use) are equally suitable. Václavík *et al.* (2013) construct 'land system archetypes' using a large number of indicators, many of which relate to agricultural land use intensity and socioeconomic conditions. They use a type of artificial neural network called self-organising maps to reduce the dimensionality and create broadly contiguous zones but do not evaluate the suitability of the land use.

Examples where agriculture is compared to other competing land uses include an assessment of the 'utility' of the land, measured by the net present value (economic) of the land (Koomen *et al.* 2015). Strassburg *et al.* (2014) address the likelihood of a particular land use by combining the constraints in two indices: (i) a suitability index for different land cover using FAO GAEZ maximised technological mix, and; (ii) an Economic Pressure on Land (EPL) index which incorporates calorific demand of all population centres weighted by the transport cost applied globally. The two indices were combined statistically to derive a relationship with actual land cover. This relationship was then projected into the future to produce probabilities of land conversion under different demand scenarios incorporating changes to the EPL index, and with environmental changes affecting the suitability index. Other land use models, such as the Conversion of Land Use and its Effects (CLUE) modelling framework (Verburg *et al.* 2002), include rules for conversion between different land use types. In CLUE the existing land cover is a constraint and there are defined land use transition sequences and conversion elasticities (the relative costs of conversion). Land use models often have time steps and are potentially more computationally intensive than a simple projection into the future, but necessarily need to consider both suitability for a particular land use and the likelihood of a particular land use spatially and temporally. Spatial and temporal non-stationarity is less of an issue for the biophysical assessment of suitability, but is likely to be important for likelihood, can be overcome by applying regional models, or using some kind of Geographically Weighted Regression (GWR) model (Brunsdon *et al.* 1996).

Willemen *et al.* (2010) take a different approach and look at broader landscapes and compare the multi-functional (summed) capacity of a landscape with the mono-functional capacity and show that mono-functional capacity decreases as multi-functionality increases, and vice versa. The concepts of multi-functional landscapes - within which agriculture plays various roles - or multifunctional agriculture can help to define objectives at the landscape level (Groot *et al.* 2009) which in turn will determine the appropriate measures of suitability for agriculture. Groot *et al.* (2009) also suggest that a combination of approaches and modelling tools will be needed to evaluate multi-functionality.

3.3 CHANGES IN SUITABILITY AND CHANGES IN LIKELIHOOD

Biophysical and socioeconomic determinants of agricultural suitability are subject to changes over time. These changes are important to consider when projecting scenarios of future agriculture suitability and other land uses. The objective of many recent studies is the assessment of the potential impacts of changes to the biophysical suitability of agriculture as a result of climate change (e.g. Beck 2013, Devendra 2011, Fischer *et al*. 2005, Jayathilaka *et al*. 2012, Kala *et al*. 2012, Lee 2009, Mainuddin *et al*. 2013, Parry & Swaminathan 1992, Seo *et al*. 2009a, Seo *et al*. 2009b, Tang *et al*. 2000, Tatsumi *et al*. 2011, Teixeira *et al*. 2013, Zabel *et al*. 2014). This is often tackled by looking at the requirements of specific crops and analysing changes in the areas for which they are suitable. It is difficult to compare the results of these studies because they use different Global Circulation Models (GCM), different socioeconomic scenarios of CO_2 emissions, and different future dates. For instance Beck (2013) shows that for 2050 there will be large losses of suitability in tropical humid areas, intermediate losses in maize/wheat areas, gains in rye growing areas, but with big local variations. They show that the A2a scenario has higher losses than B2a scenario. Fischer *et al*. (2005) meanwhile, consider various GCMs and simulate various dates up to 2080 based on atmospheric CO_2 levels. They show that 20-40 food insecure countries would lose 10-20% of cereal production potential. Tatsumi *et al*. (2011) concentrate on changes in staple crop yields and also use various GCMs but project forward to 2090, again showing large local variations in changes in potential yields. Looking even further forward to 2100 Zabel *et al*. (2014) estimate that the global area of land suitable for agriculture will increase, although much of this land would be only moderately or marginally suitable, with sub-Saharan Africa suffering the biggest losses in suitability. When the authors take account of potential multiple cropping, on the same piece of land, then the global area of suitable land for agriculture decreases.

Approaches based on plant physiology allow for the incorporation of changes in soil fertility or structure due to erosion, fertility mining or other forms of land degradation, however none of the continental or global studies that we reviewed actually did this, although the research design did not specifically focus on such studies. Where only the soil type or class is used in the assessment of suitability then the models will not be able to incorporate changes in soil characteristics (Tatsumi *et al*. 2011).

Conventional crop breeding or genetic modification can cause changes in the crop characteristics, for instance early maturation, increased resistance to pests and diseases, tolerance to drought or water-logging or to soil toxicities (Fischer *et al*. 2002, Lather *et al*. 2009). These factors could be incorporated in models (Perego *et al*. 2014) but we found no instances of this in our sample of studies apart from the possibility to select the length of maturity as a crop ideotype in the GAEZ database.

Process-based methods are well suited to explore changes in the biophysical suitability of agriculture because the responses of the crops or animal to the different levels of the biophysical variables are well understood and are modelled explicitly. Novel changes in the genetic structure of crops such as the introduction of the C4 photosynthetic pathway into C3 crops (like wheat and rice) would increase the efficiency of photosynthesis, and the yield potential (Wang *et al*. 2012). These novel changes are a challenge to modellers and although these plants are yet to exist there are already tools to examine the impacts of these changes (Yin & Struik 2009; Yin & van Laar 2005).

The lack of a theoretical model in data-driven empirical approaches will hamper their potential to model suitability for novel environments (Overmars *et al.* 2007). Empirical models are also sensitive to the historical circumstances that cause a particular spatial pattern of land use or the presence of 'agriculture', and are less able to cope with non-stationary land use change processes (Mas *et al.* 2014). The Land System representation (van Asselen & Verburg 2012) has the potential to show suitability based on relationships between existing land systems and spatial determinants. The most interesting finding of the study is the non-stationarity of the relationships at different scales and regions, however due to this fact and the perceived lack of socioeconomic data the relationships are not actually used to project into the future.

3.4 BIOPHYSICAL FACTORS USED IN THE ASSESSMENT OF SUITABILITY

We reviewed each assessment and noted the type of biophysical factor or variable that the authors used to determine the suitability of an area for agriculture. We classed the biophysical factors according to whether they affected the potential or water limiting yield of a crop, the nutrient limited yield, the reduced yield due to pests and diseases as well as factors that affect the management of the crop or which contribute to soil erosion like terrain. The most common factors were climatic, followed by soil and terrain. Very few assessments considered the effects of pests and diseases, especially at the global scale (Figure 5), and two studies (Devendra & Thomas 2002 and Chang 1968) just mention pests and diseases without proposing a way of incorporating the factor in a quantitative assessment. One study (Ewel 1999) defines broad climatic zones and suggests ways of combating biotic stresses in wet tropical areas by changing the crop micro-environment to a relatively harsher abiotic environment (by flooding) and consequently reducing the biotic stresses. The author does not seek, however, to quantify biotic stresses directly. Van Velthuizen *et al.* (1995) comprehensively consider pests and diseases, they incorporate the pest and disease frequency and severity for the dominant crops in 'crop production system zones' in eastern Africa. The authors considered a total of 44 pests and 26 diseases. Studies that use the FAO GAEZ approach will also consider pests and diseases although this is a function of the length of growing period and the level of inputs (Fischer *et al.* 2002), rather than a spatially explicit database of known presence and severity of pests and diseases.

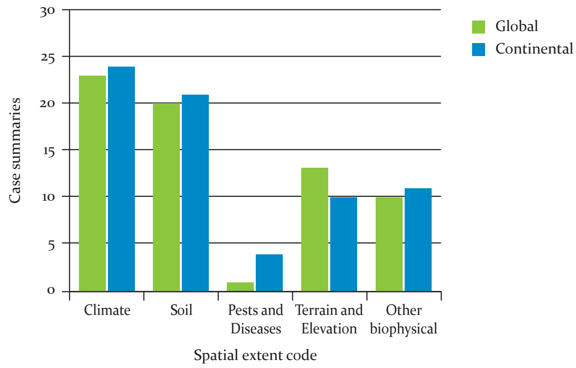

Figure 5. Number of global and continental level studies that consider types of biophysical factors.

Most of the assessments considered climatic factors, but the few that did not consider climate were characterised by an emphasis on soil (Abe *et al.* 2010), irrigation (Awulachew *et al.* 2010), existing crops (Monfreda *et al.* 2008, Fischer *et al.* 2010, Ramankutty *et al.* 2002b), existing livestock (Seré *et al.* 1995), or they were adding additional criteria to existing AEZ (Gryseels *et al.* 1992, Lambin *et al.* 2013).

The majority of studies at the global and continental scale consider soil properties except where there is a purely climatic assessment such as relating to the effects of climate change (Carter *et al.* 1991), or the proportion of primary productivity appropriated by humans (Imhoff *et al.* 2004).

3.5 NON-BIOPHYSICAL FACTORS

Far fewer studies consider socioeconomic factors in their assessments of agricultural suitability compared to biophysical factors. Of the three factors that we searched for explicitly, the most common was land tenure, land size or some aspect of the cropping system (Figure 6). Beets (1978), for example, makes reference to the agronomic practices of southern and eastern Africa in the 1970s and highlights that past production may have been land inefficient but was sufficient to feed the population as well as to provide a surplus, however with population increases those practices were no longer sufficient to feed the population. The study puts management practices in a genotype-by-environment conceptual framework but does not attempt to quantify the effect of these practices on reducing the yield gap for crops. The concept of carrying capacity expounded by Christiansen (1979), linked the suitability of an area for agriculture with its potential to support a population, but recognised that carrying capacity was only a relevant concept for either global calculations or for closed systems where there is no trade in food.

Lambin *et al.* (2013) tackle directly the main constraints to the conversion of non-agricultural land into cropland and provide a useful typology under four groupings: social, political, economic and physical. They addressed these constraints for case studies in regions where previous assessments identified large areas of land suitable for conversion to agriculture. In each case study the socioeconomic constraints were slightly different, for instance in the Chaco region of Argentina, policies on land tenure for foreigners place a barrier on conversion, while in the Cerrado region of Brazil, lack of transport infrastructure and labour are constraints to conversion. In the Brazilian and Bolivian Amazon region, labour is again a constraint to conversion from ranching to agriculture, as well as formal protection. The authors consider transportation less of a barrier than in the Cerrado although they do not consider mature intact forest as potentially cultivable land despite its suitability. Socioeconomic constraints in the Democratic Republic of the Congo (DRC) were similar to the Cerrado of Brazil but conversion would be further complicated due to the weakness of the state and frequent conflicts, especially in eastern DRC. In Indonesia, constraints to conversion of already deforested lands included transaction costs where local communities have informal claims on cleared land, whereas access to processing plants differs according to location. The final case study was Russia where barriers to conversion include poor access to markets in Siberia and insecure land tenure in European Russia. These studies illustrate that the diversity of constraints to conversion varies according to the context and highlight the difficulty of including these dynamic factors in a global assessment of suitability or likelihood of conversion of non-agricultural land. Nevertheless, some assessments use scenarios which include macro-socioeconomic drivers of demand such as changes in labour, technology, consumption patterns, trade prices and risk of hunger and link these with the biophysical factors that determine the suitability of individual crops (Fischer *et al.* 2005).

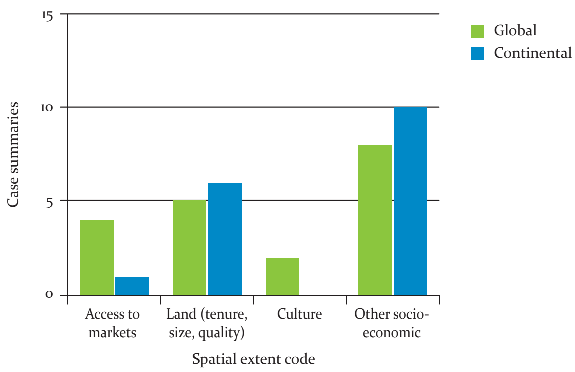

Figure 6: Number of global and continental level studies that consider types of non-biophysical factors

3.6 SUITABILITY ZONES

The creation of zones is not a necessary precondition for assessing the suitability for agriculture which can be calculated for any location or pixel for which data are available (e.g. GAEZ). Nevertheless a number of the assessments we reviewed defined zones to help design future research, or to make results more understandable to lay audiences. Studies sought to create zones based on either current suitability for agriculture, future suitability for different crops or systems, or did not seek to define zones (Figure 7).

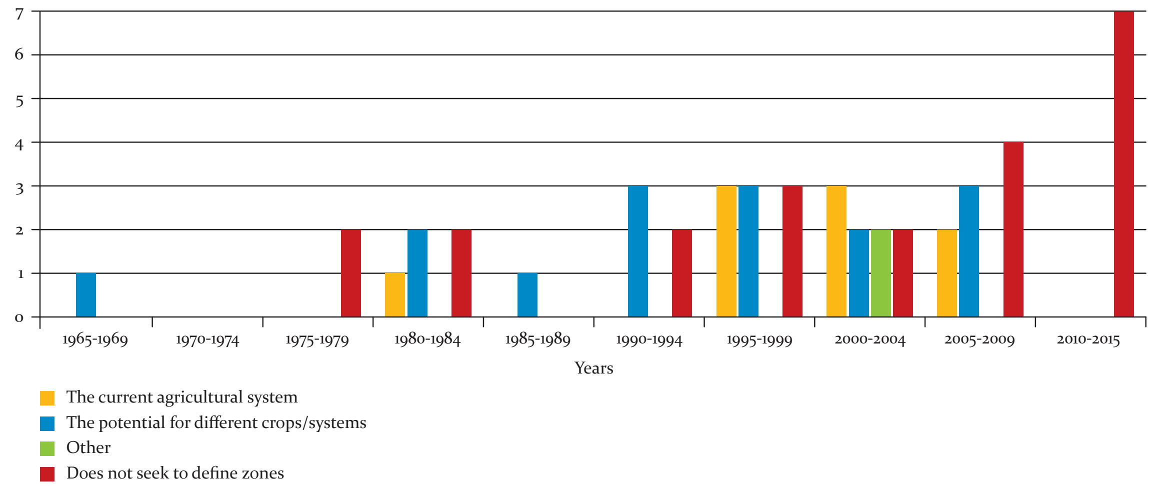

Figure 7: Basis for zoning in global and continental level studies over time

Van Velthuizen *et al.* (1995) produce crop production system zones for eastern Africa by combining three variables – temperature, moisture regimes and seasonality/irrigation – with agro-climatically relevant thresholds to stratify the variables and produce a matrix of zones. These zones are subsequently mapped onto administrative areas and are further characterised according to environmental hazards, pests and diseases etc. Wortmann and Allen (1994) produce a similar matrix, albeit related to a specific crop and including soil constraints, they also augment these zones with more detailed zonation (Wortmann *et al.* 1998) based on socioeconomic and cultural factors to move from crop suitability to actual crop production areas.

Both White *et al.* (2001) and van Wart *et al.* (2013) produce zones for prioritising research. In the latter, the authors provide a useful review of methods of zoning using just agro-climatic variables. They differentiate matrix zonation schemes (like Wortmann & Allen 1994, White *et al.* 2001, Van Velthuizen *et al.* 1995) with cluster zonation which produces a fixed number of zones based on potentially numerous variables. Metzger *et al.* (2013) for instance, ran a principal components analysis (PCA) of 36 climatic variables and selected four. The authors ran a further PCA on these four climatic variables and clustered the PCA components into 125 strata, which were then aggregated into 18 global environmental zones. Problems with such schemes include difficulties in validation and interpretation for assessing suitability. A similar data-driven approach was applied by Václavík *et al.* (2013) who produced a map of 12 land systems using a self-organising map (SOM) algorithm—a form of artificial neural network. The land systems allowed for similar systems to be identified across national borders while retaining heterogeneity within countries.

3.7 SPATIAL RESOLUTION

The spatial resolution indicates the precision of the suitability assessment, with a higher resolution (or higher granularity) allowing a better discrimination between different localities that are close to each other. Very precise assessments do not imply accuracy (Avellan *et al.* 2012) but high-resolution is especially useful for parts of the world that have large gradients over small distances in temperature (due to elevation), rainfall or soil types. The most common level of resolution for global and continental scale assessments is a medium resolution (Table 4), which can provide a suitability value for an area between 5 km^2 and 50 km^2. Many studies, however, do not provide information on the resolution of the assessment or are a mix of different resolutions. For example, Seré *et al.* (1995) characterise pre-existing agro-ecological zones according to indicators that are specific to livestock systems, the resolution in this case depends on the original data used to define the zones.

Table 4: Number of studies per class of spatial resolution

Spatial Resolution	Number of studies
Low Resolution (> 30' or 50km^2)	11
Medium Resolution (2.5'-30' or 5-50km^2)	17
High Resolution (< 30' or 5km^2)	5
Site specific	1
No information or mix of resolutions	23

Assessments that use remotely sensed data to identify or describe zones of suitability have benefited in recent years from an increase of sensors that can produce higher resolution data and increased computer-processing power. The availability of high-resolution land cover and climate data since 2000 has resulted in higher-resolution assessments, even at the global and continental scale (Table 5). However, the studies that use these data often have to contend with a mixture of resolutions (e.g. Fischer *et al.* 2010), and care must be taken when interpreting assessments that combine data of varying resolutions. Scale dependence, which has been shown to affect the interactions between the variables that affect the suitability for agriculture (Evans & Kelley 2004), can be modelled in inductive approaches by performing multiple stepwise regression at a range of scales (Wassenaar *et al.* 2007). Some land use models (e.g. Schaldach *et al.* 2011) incorporate factors that affect the suitability of agriculture but at a lower resolution than the final allocation of different land uses; this can have the advantage of retaining accuracy where climate data are at a coarser resolution than terrain (Nguyen *et al.* 2015)

Zabel *et al.* (2014) developed an approach to mapping agricultural suitability at the global scale using the AEZ principle at a finer resolution (30 arc seconds or ~ 1 x 1 km) and considering the start of the growing season as well as number of crop cycles.

Table 5: Number of studies in 5 year periods for each class of spatial resolution

	Low Resolution (> 30' or 50km²)	Medium Resolution (2.5'-30' or 5-50km²)	High Resolution (<2.5' or 5km²)	Site specific	No information or mix of resolutions
1965-1969					1
1970-1974					
1975-1979	1				1
1980-1984	2				3
1985-1989					1
1990-1994	2	3		1	2
1995-1999	1	5			4
2000-2004	2	3	2		6
2005-2009	2	2	2		1
2010-2015	1	4	1		4

3.8 REFERENCE TIME PERIOD

Two aspects of the time period of assessments are important, the time period of the data that are used in the assessment of suitability and, closely related to this, the period for which the assessment is valid. Some of the factors that are used in suitability assessments are more dynamic than others; therefore, the importance of the time period of a specific assessment will change depending on the method and data used. Scientists might once have assumed climatic data static, but with increased global surface temperatures and changes in the patterns of rainfall, this is no longer the case. Some soil properties are more dynamic than others so it is also necessary to determine which properties are used in an assessment and how likely these are to change over time. Soil depth may reduce over time due to erosion, texture is unlikely to change across the whole profile unless there are amendments to improve texture or where compaction can degrade texture. Soil amendments can also modify pH and drainage can be improved or impeded. The crop characteristics also change over time due to efforts to breed varieties which are more tolerant of stresses or which have a higher yield potential. Non-biophysical factors, such as land tenure, trade, regulatory frameworks or access to markets are also dynamic and their importance may change over time.

Table 6: Number of studies in distinct reference time periods

Time period	pre 1960	1960-1990	1990-2015	2015-2100
# of assessments	3	20	34	6

* includes additional studies in snowball sample

With this in mind it is important to specify the period for which the input data are representative or valid. Of the 86 global and continental assessments, the most common reference period is between 1990 and 2015, followed by the period between 1960 and 1990 (Table 6). This is consistent with the general increase over time of suitability assessments and suggests that studies use the most up-to-date data, including projections for future climates that have become more widely available over the past ten years and at higher spatial resolutions (e.g. climate model data available at CCAFS or IPCC Data portals). Global circulation models of climate are often combined with or are based on scenarios of economic development. These scenarios include projections of trade and demand for agricultural products, which will not affect the biophysical suitability for agriculture but affect the likelihood of land being exploited for specific crops or agriculture in general (e.g. Fischer *et al*. 2005). We argue that studies that take into account non-biophysical factors are more sensitive to temporal non-stationarity, where the relationships between determinant factors and suitability change over time (Wrenn & Sam 2014). Without access to historical datasets, however, it is difficult to account for temporal non-stationarity in the determinants of agricultural suitability.

Changes in soil properties are far more difficult to model than changes in climate, although developers could create scenarios that incorporate potential soil dynamics and evaluate the impact of these changes (e.g. Sun 2011).

3.9 ORGANISATION(S) INVOLVED IN AGRICULTURAL SUITABILITY ASSESSMENTS

The organisations that were involved in producing or using assessments of suitability at the global and continental scale included both national and international organisations. Thirteen of the 81 studies were multiple-partner collaborations, while single organisations produced twenty-eight studies. We were unable to find information on the organisation for the remaining twenty-six studies.

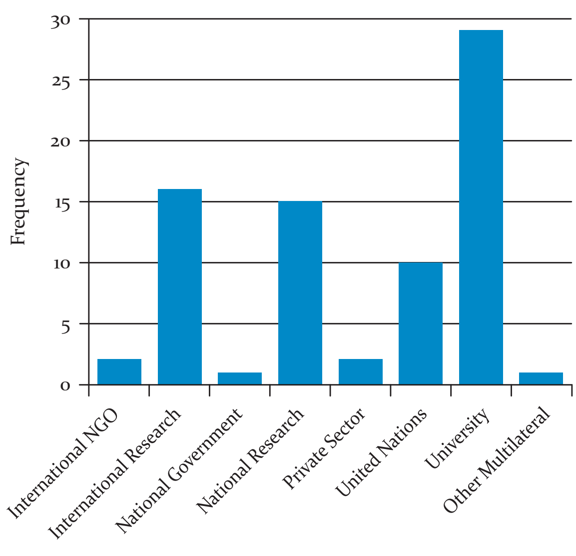

Figure 8: Frequency of different types of organisations producing or using global and continental suitability assessments

The types of organisations ranged from national governmental to United Nations organisations. The most common organisations producing suitability assessments were universities, followed by international and national research organisations (Figure 8).

The results are not surprising as the focus on continental and global studies are of most relevance for organisations that have an international mandate. United Nations organisations included the Food and Agriculture Organization (FAO), the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The large number of national research institutes includes many European and US research institutes that have links to universities.

3.10 NATIONAL AND LOCAL SCALE ASSESSMENTS

While we prioritised global and continental studies there were some studies at the local and national levels that used different methodologies, or had objectives which could potentially be adapted for larger spatial extents.

Linkages to particular interventions, policies or to land planning were common in national studies. Feizizadeh and Blaschke (2013), for instance, use multi-criteria evaluation of land suitability based on local expert knowledge in which different criteria are weighted according to their perceived importance. These are the same factors as those included in other methods (such as GAEZ) but they do not contribute to a production function. Thresholds can be applied to give binary classes, or a fuzzy membership set (e.g. Abbaspour *et al.* 2011) can be defined for each of the factors. In this latter case the authors use Analytical Hierarchy Process (AHP) to determine the weights with relative importance identified by expert knowledge. They are able to create suitability maps for different kinds of agriculture and compare with actual land use to show areas suitable but not currently exploited. This method is less useful for global studies where the relative importance of factors may not always be consistent over large spatial extents.

Jayathilaka *et al.* (2012) like Feizizadeh and Blaschke (2013), use AHP to determine weights in a multi-criteria evaluation of suitability for three plantation crops. They use two historical time frames and compare changes in suitability with changes in actual yields over the same period. This comparison was possible given the presence of weather data from meteorological stations as well as yield records from the plantation estates, a situation unlikely to be replicated in other contexts and for other crops.

Mendas and Delali (2012) also use a multi-criteria decision analysis (MCDA) tool to assess suitability for durum wheat in Algeria. They include socioeconomic factors in their assessment (labour and proximity to roads), but because of the small extent of the study they do not consider climatic factors.

Liu *et al.* (2011) take into account various criteria for agricultural suitability including compactness. This is a factor which is often ignored in other studies and relates to management and the landscape value of non-fragmented farmland (in China). They optimise for multiple planning objectives using an algorithm inspired by immune systems, whereas Neto *et al.* (2011) use genetic algorithms.

Agrell *et al.* (2004) use a national AEZ database as an input in a decision support system for agricultural land use planning in a region of western Kenya; additionally they take into account labour, other costs, and the values of individual crops. They have numerous objectives related to maximum production of food, food self-sufficiency, erosion and income. Many of the objectives are conflicting, implying an analysis of trade-offs, different solutions are presented iteratively to a decision maker, with selections forming the basis for subsequent iterations.

A number of national studies sought to combine various different methodologies to assess suitability. Confalonieri *et al.* (2013) create a suite of software tools for assessing suitability, incorporating both empirical (what they call multi-cell suitability approaches) with methods based on environmental envelope models (EcoCrop), GAEZ type process models, or direct crop suitability discriminant. They allow users to select and to mix different strategies (from the approaches) and also to add other components. Tian *et al.* (2012) combine the Decision Support System for Agrotechnology Transfer (DSSAT) crop growth simulation model and the AEZ approach for one crop in one country (China). They attempt to upscale the results of DSSAT by reclassifying the cropping zones based on available weather and agricultural field stations (similar to Yield Gap Atlas Strategy; van Wart *et al.* 2013). Fischer and Sun (2001) combine three methodologies to move from agricultural suitability using the GAEZ approach to land use optimisation for the whole of China.

The treatment of trade- offs was explicit in many of the multi criteria evaluations. Pineda-Martinez *et al*. (2013) look at the trade-offs between food self-sufficiency and agricultural production sustainability while the objective of Reed *et al*. (2013) was to explore the impacts of two agricultural production scenarios (extensification and intensification) on ecosystem services and identify trade-offs. This was carried out over a small area and the ecosystem services were easy to identify; this would be more difficult for a larger area. The potential impact of changing suitability for specific crops on protected areas was assessed by Bradley *et al*. (2012) in South Africa. They use an ecological niche model to determine suitability for two crops, using very accurate crop presence, soil and climate data.

4. Discussion and conclusions

The majority of the assessments in this review were identified by a systematic search of peer-reviewed literature, but we added further studies based on references in the original selection. We also reviewed other assessments that had not been identified during the initial literature search due to either the time difference between initial selection of papers and further analysis (July 2013 – February 2015) or the search terms that were originally used. For instance, there is a significant body of work on land use models that discusses the suitability of land for various purposes but which may not include the term 'agriculture' in the title, abstract or key words. These models are discussed in a separate review of land use change models which is intended to be used in conjunction with this review (see van Soesbergen 2016).

Our review of the assessments was guided by questions that help us to understand the range of approaches that have been used to assess suitability and the most appropriate methods and data according to the purpose of the assessment. The most fundamental characteristic of the assessments was the reasoning behind the method to measure or predict suitability of agriculture. We identified five broad methods that included approaches based on plant physiology and/or approaches based on socioeconomic and biophysical factors.

Approaches based on plant physiology, which include process-based models, such as the FAO GAEZ methodology, tend to focus on the biophysical requirements of specific crops and take advantage of recent improvements in the understanding of crop physiology that drives many crop growth simulation models and the continuous improvements of spatial data on biophysical factors. The results of these models (e.g. biomass, grain yield) are easily comparable between crops and can be converted to other metrics like income, calories or protein. The models can also include scenarios of management practices, soil nutrient management and crop protection. Empirical models, such as ecological niche models, were fewer in number but represent a different way of considering suitability, one that considers agriculture and particular crops as a part of an ecosystem in which there is competition between plants and land uses. In their treatment of niches these methods must necessarily consider suitability as just one component of the likelihood of a particular land use at a particular location at a particular time.

Approaches based on socioeconomic and biophysical factors of suitability recognise the importance of human agency. These approaches judge suitability as the result of many decisions which may or may not be optimal. They go further than ecological niche models and include factors affecting the feasibility of a particular land use or cropping system. Trade-offs were often explicitly considered in these approaches because of the recognition that intensification of agriculture or conversion from other uses have environmental and social costs that must be considered.

4.1 SUITABILITY FOR AGRICULTURE OR LIKELIHOOD OF AGRICULTURE

There are two important objectives when assessing the suitability of land for agriculture. The first is to provide information that can potentially be used to calculate the amount of food, fibre, feed and other agricultural products that can be produced on the planet, in effect defining the human carrying capacity of the earth (Cohen 1995). This objective requires identifying (i) areas which are suitable for agriculture but which are not exploited; (ii) areas where agriculture is currently practised but which are not suitable; and, (iii) areas where the agricultural productivity is lower than it could be. The second objective, which we cover in more depth in a review of land use change models (van Soesbergen 2016), is to determine the likelihood of conversion of land to or from agriculture or the likelihood of intensification of production, based on the current and future suitability of land, and the current and future drivers of allocation of land.

In essence the first objective is to define the potential agricultural production while the second assesses the options for reaching the potential and can be used to develop scenarios of future agricultural production and land use.

The first objective will help firstly to evaluate trade-offs or synergies between biodiversity and/or ecosystem services values with agricultural production in scenarios where areas that are currently suitable but not used would be converted to agriculture, by comparing existing and potential agricultural land use and assessing the potential impacts of conversion or intensification. Secondly, it will help to identify areas that may have higher value for biodiversity and ecosystem services if restored to natural vegetation than under their current unsuitable use or where productivity may be boosted to avoid conversion of neighbouring areas (Grau *et al*. 2013). Identification of these areas can then lead to an assessment of the socioeconomic reasons for why agricultural production exists on unsuitable land or why productivity is low. Such analyses can inform decision-making as to the most efficient or sustainable use of land for agriculture and other land uses providing other ecosystem services (notwithstanding that there may be socioeconomic factors preventing such pure "efficiency-maximization"). For an overview of approaches to mapping ecosystem services, see Burgess *et al*. (2016).

The second objective helps to develop maps of increasing or decreasing "pressures" on biodiversity and ecosystem services from likely future uses of land. Together with information on the synergies and trade-offs that such changes would imply (and for whom), this can support the development of policy or regulation to mitigate or deflect these pressures in certain high value (e.g. for other ecosystem services) areas.

Many approaches reviewed were based on plant physiology and the theoretical response of plants to external stimuli like temperature, solar radiation, water, carbon dioxide and other nutrients. The spatial distribution of the availability and quantities of these stimuli, and the interactions between them, determine the assessment of suitability for specific crops. Crops are not grown in isolation, however, and these assessments will only be useful for informing about potential agricultural production when they are put into the context of farming systems. For this reason we see a constant adjustment of these methods to include factors that better reflect actual cropping systems, but as yet we do not see novel (Koning & van Ittersum 2009, Overmars *et al*. 2007) or complex production systems (such as agroforestry) incorporated.

Empirical models e.g. models of land use change seem to be better suited for multi-sectoral land suitability, whereas approaches based on plant physiology are more often used for single sector suitability (Koomen *et al.* 2015). In models based on the presence of a particular crop or land use and using regression techniques (e.g. Beck 2013) there is an assumption that the absences are real i.e. that the crop is not in an area because it is unsuitable, whereas in reality a crop may not be in an area because there are alternative crops, because there is nobody to grow that crop, or because the crop has never been introduced to that area. Approaches that seek to determine the process behind suitability from the pattern of current land use or crop system will therefore encounter problems if they ignore all of the potential factors that cause the pattern of land uses with niches for particular crops. Ecological literature on niches gives two definitions – firstly the niche as the environmental requirements needed for a species to subsist, and secondly as the relationship of a species to other species (Hirzel & Lay 2008). We see that the first definition is more akin to suitability for agriculture whereas the other looks at the competition between crops or between different uses of land and includes factors that may not strictly be environmental.

There are also many recent studies that assess the potential impacts of changes to the biophysical suitability of agriculture, for example as a result of climate change (e.g. Beck 2013, Devendra 2011, Fischer *et al.* 2005, Jayathilaka *et al.* 2012, Kala *et al.* 2012, Lee 2009, Mainuddin *et al.* 2013, Parry & Swaminathan 1992, Seo *et al.* 2009a, Seo *et al.* 2009b, Tang *et al.* 2000, Tatsumi *et al.* 2011, Teixeira *et al.* 2013, Zabel *et al.* 2014). These studies use socioeconomic scenarios of CO_2 emissions to predict changes in agricultural suitability based on the requirements of specific crops. However, as the socioeconomic scenarios, Global Circulation Models (GCM) and timescales often differ, comparison between study results is difficult. The review found process-based methods are well suited to exploring the changes in biophysical suitability of agriculture because the responses of the crops or animal to different levels of the biophysical variables are well understood and are modelled explicitly. However, the potential of empirical models to assess suitability in novel environments is limited by historical patterns of change and cope less well with non-stationary land use change processes (Mas *et al.* 2014).

Changes in the socioeconomic determinants of the cultivation of a particular crop or of agricultural land use are also likely to change over time e.g. population rise, changes in diet and the use of land for non-food crops (Mauser *et al.* 2015, Cirera & Masset 2010, Kearney 2010, Pelletier & Tyedmers 2010, Gerbens-Leenes *et al.* 2010, Koning *et al.* 2008). The amount of land required for food production (and its crop composition) will depend on commodity trade and the distribution and waste of food (Godfray *et al.* 2010, Narayanan & Gulati 2002; Godfray 2011, Gustavsson *et al.* 2011). At the same time there will be competition for land from other land uses such as urban areas (Cohen 2004, Young 1999). These determinants can be modelled explicitly as part of a food system (e.g. Fischer *et al.* 2005, Lee 2009) or aggregated into demand scenarios (e.g. Wassenaar *et al.* 2007, Eitelberg *et al.* 2014) which are a useful tool for explaining potential futures but only cover a small fraction of all possible futures (Groot *et al.* 2009).

4.2 INDIVIDUAL CROPS, FARMING SYSTEMS OR 'AGRICULTURE'

In the context of African smallholder farmers, Tittonell *et al*. (2009) discuss the 'ideal farm', which takes into account resource efficiency of land, labour and nutrients and the sustainable accomplishment of farm objectives. The ideal farm is the most 'suitable' configuration to balance the competing demands of food security and income generation while at the same time conserving soil fertility status. Nevertheless, the most suitable farm configuration often changes according to the wealth of the farm household (Zingore *et al*. 2009). It is worth noting that optimisation at this local scale is based on very different assumptions than optimisation at global, regional and national scales. Optimisation at larger scales is often less explicit but still depends on these local level decisions which affect land use. A practice which operates over multiple levels in the farming system is conservation agriculture, which has been shown to have great promise for increasing the resilience to low soil moisture and nutrient deficiencies, but which often fails to have a long-term impact. The suitability for this particular practice has been assessed agronomically but also considering socioeconomic factors (Rosenstock *et al*. 2014).

The challenge for global studies of agricultural suitability is how to incorporate the complexities of multiple farm systems (i.e. systems within the same land use class) with competing production and other environmental/socioeconomic/ political objectives in a pixel or zone. Methods using weights to estimate the likelihood of a particular crop in a particular location (e.g. You *et al*. 2014 and Fisher *et al* 2002) are useful but would need to be expanded to consider the competition between 'agriculture' and other land uses or livelihood strategies at larger scales. Examples where agriculture is compared to other competing land uses include assessments of the 'utility' of the land, measured by the net present value (economic) of the land as well as studies into the multi-functional (summed) capacity of a landscape versus capacity of mono-functional landscapes. The concepts of multi-functional landscapes - within which agriculture plays various roles - or multifunctional agriculture can help to define objectives at the landscape level which in turn will determine the appropriate measures of suitability for agriculture.

Ultimately the primarily global and continental scale of the studies that we looked at in detail are not appropriate for assessing farm systems and household level decision–making. For decisions at this level, global principles of mapping agricultural suitability will need to be supplemented by a review of relevant local studies within landscapes.

4.3 CONCLUSIONS

In this review we focused on global and continental level assessments, however to assess agricultural suitability at the national level we advise consulting local and national studies, verifying the methods, the criteria used, and the data quality. For this purpose we provide a database of all the studies that have been documented in peer-reviewed journals considered in this review (see Appendix 2).

We have shown that there has been an ever increasing number of assessments of the suitability of agriculture with especially more local and national studies. With better access to data and wider sharing of methods it is now easier than ever to conduct an assessment. This is welcome given the global pressure on land for agricultural products.

The vast majority of global and continental studies use approaches based on plant physiology, particularly those that use process-based models. The most common methods used FAO Agro-Ecological Zones models. The AEZ method is intuitive and calculates different yields (potential, water limiting etc.) for a large number of crops as well as modifying the suitability according to terrain. Due to the strong theoretical links to crop physiology the methods are able to cope with novel future environments which have no current analogue. In order to assess the likelihood of agriculture at any particular place and time the agronomic suitability assessments using the AEZ methodology need to be complemented with additional biophysical, socioeconomic or institutional constraints that may affect potential land use.

Although, within the scope of our literature search, we found relatively few approaches based on empirical models (whereby process is inferred from spatial and temporal pattern) these methods are common in land use models. A separate review which forms part of this suite of reviews looks specifically at land use change models (van Soesbergen 2016). Assessments using empirical models consider all of the factors that determine the use of land, but often have difficulties in determining the cause of the pattern due to data availability. These deficiencies are being overcome by better specification of the models using more local knowledge, the increasing availability of data (e.g. 'Big Data') as well as combination with process-based models in modular structures. Empirical models also encourage analysts to think in terms of niches. Studies that combine actual cropping systems, suitability for distinct crops, local factors that favour particular crops or land uses and scenarios of global demand would appear to offer the most complete assessment of the likelihood of conversion of land to different crops or from non-agriculture to agriculture.

We noted a gradual increase in the spatial resolution of the global and continental studies over time, although studies at the highest resolution (<5 km^2) are still not common. This is probably due to the lack of extremely high resolution climate data which are arguably the biggest drivers of agricultural suitability, or of data of functional soil properties (such as soil pH). The resolution of the assessment should relate to the system that is being assessed and the drivers/determinants, and the measure of suitability should be consistent. We observe that common measures of suitability relate to plant biomass, or attainable yield, both of which are plot level outputs. However when assessing suitability for medium resolutions of 5–50 km^2, each pixel could represent a farming system or a landscape instead of a single crop, but there are as yet no measures of agricultural suitability that consider such system levels, although there are some studies which look at landscape systems not specific to agriculture (e.g. Van Asselen & Verburg 2012).

The creation of agro-ecological zones as part of an assessment of agricultural suitability is becoming less common for global and continental level studies. Zones are good communication tools and are useful for planning research and developmental interventions, as well as for simple statistical analyses. Zones are less useful, however, for combining different datasets and many studies have shown that zones often mask heterogeneity in factors that are important for agricultural suitability and the likelihood of land conversion or land degradation.

Many studies have highlighted the importance of taking into account the dynamism of the factors that affect, to a lesser extent, the suitability of agriculture, and to a greater extent the likelihood of land being used for agricultural production. Dynamism of biophysical agricultural suitability is related mainly to changes in climate. Estimates of these changes are now widely available and are relatively easy to handle for process-based models. In contrast the huge range of contextual factors that 'cause' land to be used in a certain way or for crops to be adopted is possibly the biggest hurdle for both process-based and empirical models. Land use models which simulate patterns over many time steps and for large spatial extents have made much progress in resolving issues of spatial and temporal non-stationarity. We see that there are also many novel methods at the national and local levels related to land use planning which could be incorporated into global and continental studies but the challenge will be to reconcile decision-making at multiple levels, volatility of macro-economic drivers of land use, and fundamental changes to the biophysical environment.

5. Recommendations

This report provides an overview of the most commonly used approaches to mapping agricultural suitability, focusing on global and continental scale assessments. The recommendations provided here should be considered alongside a suite of other technical reviews which form part of this body of work on supporting an ecosystem-based approach to agricultural development policy and planning. Reviews include those on ecosystem services mapping, biodiversity mapping, scenario development and land use change models.

The summaries of approaches to mapping agricultural suitability are intended to increase capacity to understand and use such approaches by national and sub-national level decision makers. The other considerations highlighted in the results are also intended to allow decision makers to make informed choices around whether to use existing assessment results or develop a new assessment tailored to the question or region of interest. However, as this review focuses on large scale assessments, primarily based on process-based models, challenges can arise when generalising such findings to inform national and sub-national level decision-making. We recommend that decision makers supplement the findings of this review with a review of relevant local scale assessments which are relevant to the particular landscape of interest. Nevertheless, there are a number of recommendations and considerations which are important to consider across all scales of assessment, these are proposed below.

Evaluating trade-offs and risk

1. Determining potential agricultural production and identifying other ecosystem services will help to (i) evaluate trade-offs or synergies between agricultural production, biodiversity and other ecosystem service values in scenarios where areas that are currently suitable but not used would be converted to agriculture, and (ii) identify areas that may have higher value for biodiversity and ecosystem services.

2. Determining the likelihood of conversion of land to or from agriculture or the likelihood of intensification of production will help to develop maps of potential increasing or decreasing "pressures" on biodiversity and ecosystem services from likely future developments.

3. Particular attention should be paid to a number of studies we have identified that produce an index of shared suitability which denotes potential conflict areas where different types of strategies (and land use) are equally suitable. These approaches are useful in evaluating trade-offs and risks.

Approaches

4. Empirical models that seek to determine the process behind suitability from the pattern of current land use or crop system seem to perform better for multi-sectoral land suitability, whereas process-based models are more often used for single sector suitability. Empirical models must therefore take into account all of the potential factors that cause the pattern of land uses with niches for particular crops.

5. A dynamic approach to soil and/or land degradation should be taken in suitability assessments, particularly when projecting suitability into the future. Degradation will reduce future agricultural suitability and is not currently considered in global assessments.

Data, methods and scale

6. Studies that offer a more complete assessment of the likelihood of conversion of land to different crops, or from non-agriculture to agriculture, generally include those that combine: actual cropping systems; suitability for distinct crops; local factors that favour particular crops or land uses; and scenarios of global demand.

7. We recommend that AEZ studies should combine both biophysical and socioeconomic factors that affect land use, such as Fischer *et al.* (2005).

8. Agro-ecological zones are a good communication and planning tool but are less useful for combining different datasets and mask heterogeneity in factors that are important for agricultural suitability. We recommend the highest possible spatial resolution is used and the appropriate measures of suitability for that resolution.

9. Global scale assessments of the likelihood of conversion and potentially of the biophysical suitability for agriculture will be affected by factors that are likely to change according to location. We recommend that locally relevant indicators are used, in multiple regional models. This type of modelling approach may help bridge the gap between local relevance and global coverage.

10. If agricultural suitability needs to be assessed at the level of a particular country we advise consulting local and national studies, verifying the methods, the criteria used, and the data quality.

Suitability of agricultural systems or crops

11. We have yet to see a measure of suitability that considers the landscape or community levels of farming systems, despite the fact that this is a common resolution of suitability assessments. We recommend working with organisations conducting suitability assessments to develop measures which best reflect farming systems instead of single crops.

12. Further research is needed and should be supported on the assessment of the suitability for complex agricultural production systems (such as agro-forestry or novel bio-based), the implications for agricultural production over large areas, and the conditions that affect the likelihood of conversion.

13. Crop-specific assessments will be useful when considering a specific crop that has a growing demand, or which has been shown to be suitable in areas which also currently provide other important ecosystem services.

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7. Appendices

7.1 APPENDIX 1. LITERATURE SEARCH AND SCREENING

The universe of literature was primarily peer-reviewed articles in SciVerse's Scopus (https://www.scopus.com/) and ISI's Web of Science (http://apps.webofknowledge.com) databases; we also consulted grey literature in Google search.

A1.1. Searching in title, abstract and keywords

We applied objective screening using keywords, which we based on the purpose of this review.

Search results (11/07/2013)

Key word	Scopus	Web of Science
"Suitability for agriculture"	30	15
"Agricultural Suitability"	58	33
"Potential for agriculture"	38	24
"Agricultural Potential"	438	231
"Agro-ecological zone" or "Agro-ecological zone*"	651	482
"AEZ" or "AEZ*"	89	143
"Agro-climatic zone" or "Agro-climatic zone*"	255	181
"Primary Production"	92,264	24,839

A1.2 Positive screening by subject/research area:

We applied objective screening using research areas or academic disciplines that are relevant to the purpose of this review.

Scopus	Web of Science
Agricultural and Biological Sciences	Agriculture
Computer Science	Biodiversity Conservation
Decision Sciences	Computer Science
Earth and Planetary Sciences	Environmental Sciences Ecology
Economics, Econometrics and Finance	Forestry
Environmental Science	Geography
Multidisciplinary	Meteorology Atmospheric Sciences
Social Sciences	Plant Sciences
	Physical Geography
	Remote Sensing
	Water Resources

Search results (11/07/2013)

Key word	Scopus	Web of Science
"Suitability for agriculture"	29	14
"Agricultural Suitability"	56	27
"Potential for agriculture"	34	19
"Agricultural Potential"	399	172
"Agro-ecological zone" or "Agro-ecological zone*"	594	396
"AEZ" or "AEZ*"	73	66
"Agro-climatic zone" or "Agro-climatic zone*"	212	126
"Primary Production"	37,184	12,028

A1.3 Positive screening by general usefulness:

A subjective screening using the titles and abstracts of the sources based on the usefulness for the purpose of this review.

Search results (11/07/2013 & 12/07/2013)

Key word	Scopus (non-duplicates)	Web of Science
"Suitability for agriculture"	0	6
"Agricultural Suitability"	6	14
"Potential for agriculture"	5	6
"Agricultural Potential"	43	33
"Agro-ecological zone" or "Agro-ecological zone*"	51	88
"AEZ" or "AEZ*"	16	42
"Agro-climatic zone" or "Agro-climatic zone*"	5	21
"Primary Production"		

We omitted results for "Primary production" because the search generated too many results. After we aggregated the citations and removed the duplicates, there remained 244 citations.

A1.4 Classification by themes:

A subjective classification using the titles and abstracts of the sources based on the purpose and methodology of this review. We only considered the first two categories of papers for further analysis.

Theme	Results
Papers that describe the development of agro-ecological zones or assessments of suitability	136[1]
Papers that refer to existing zones or assessments	87[2]
Papers that discuss general conditions for agricultural intensification or adoption of technologies (leading to intensification or land conversion)	19

A1.4.1 Analysis of papers that address methods to develop AEZ or other suitability assessments

The 136 studies reviewed sought to create zones based on either current agricultural systems, the potential for different crops or systems or did not seek to define zones of the 136 papers 15% are global, 20% are regional/continental, 37% are national/provincial and 26% are local, while the rest are pure methods papers.

Global	20
Continental	27
National	50
Local	35
Not applicable	4

	Global	Continental	National	Local	Not applicable
1965-1969	1				1
1970-1974			1		1
1975-1979	1	2			
1980-1984	2	5	6	1	
1985-1989		4	4	1	
1990-1994	3	6	9	2	
1995-1999	5	1	6	7	
2000-2004		3	2	3	1
2005-2009	4	1	10	11	1
2010-2013	3	6	12	10	

[1]One paper, THIOMBIANO, L. & ANDRIESSE, W. 1988. Research priority setting by a stepped agro-ecological approach: Case study for the Sahel of Burkina Faso. NJAS - Wageningen Journal of Life Sciences, 46, 5-14, was incorrectly dated in the Scopus database and was a duplicate of the following paper: THIOMBIANO, L. & ANDRIESSE, W. 1998. Research priority setting by a stepped agro-ecological approach: case study for the Sahel of Burkina Faso. Netherlands Journal of Agricultural Science, 46, 5-14. The paper was removed from the list.

[2]One paper, HOCHMAN, Z., GOBBETT, D., HOLZWORTH, D., MCCLELLAND, T., VAN REES, H., MARINONI, O., GARCIA, J. N. & HORAN, H. 2012. Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia. Field Crops Research, 136, 85-96, was incorrectly dated in the Scopus database and was a duplicate of the following paper: HOCHMAN, Z., GOBBETT, D., HOLZWORTH, D., MCCLELLAND, T., VAN REES, H., MARINONI, O., GARCIA, J. N. & HORAN, H. 2013. Reprint of "Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia". Field Crops Research, 143, 65-75. The paper was removed from the list.

A1.4.2 Analysis of papers that make reference to existing methods

Of the 87 papers that we reviewed, 47 made reference to other books, journal articles or reports that discussed or described methods of or related to the determination of agricultural suitability or potential. There was some duplication of references, especially those that referred to global studies such as those developed by FAO or IIASA but there were 87 unique references. 31 of the papers did not refer to methodological sources, and we could not access nine papers.

Only seven of the 87 references were in the list of papers that address methods found in the original systematic search of literature.

Global	16
Continental	18
National	34
Local	7
Not applicable	7

	Global	Continental	National	Local	Not applicable
1960-1964			1		
1965-1969	2	1			1
1970-1974		1		1	
1975-1979		2	1		
1980-1984	2	2	4	2	
1985-1989		1	2		1
1990-1994	2	3	3	1	1
1995-1999	2	4	7	1	2
2000-2004	6	3	6	1	1
2005-2009	2	1	8	1	1
2010-2013			2		

7.2 APPENDIX 2. DATABASE OF THE STUDIES IN PEER-REVIEWED JOURNALS CONSIDERED IN THIS REVIEW

The database, in the form of an Excel table, is available with the online version of this report.

www.unep.org

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: publications@unep.org
www.unep.org

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