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Review

A Review of Swidden Agriculture in Southeast Asia

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Abstract: Swidden agriculture is by far the dominant land use system in the mountainous regions of Southeast Asia (SEA). It provides various valuable subsistence products to local farmers, mostly the poor ethnic minority groups. Controversially, it is also closely connected with a number of environmental issues. With the strengthening regional economic cooperation in SEA, swidden agriculture has experienced drastic transformations into other diverse market-oriented land use types since the 1990s. However, there is very limited information on the basic geographical and demographic data of swidden agriculture and the socio-economic and biophysical effects of the transformations. International programs, such as the Reducing Emissions from Deforestation and forest Degradation (REDD), underscore the importance of monitoring and evaluating swidden agriculture and its transition to reduce carbon emission due to deforestation and forest degradation. In this context, along with the accessibility of Landsat historical imagery, remote sensing based techniques will offer an effective way to detect and monitor the locations and extent of swidden agriculture. Many approaches for investigating fire occurrence and burned area can be introduced for swidden agriculture mapping due to the common feature of fire relatedness. In this review paper, four broad approaches involving spectral signatures, phenological characteristics, statistical theory and landscape ecology were summarized for swidden agriculture delineation. Five research priorities about swidden agriculture involving remote sensing techniques, spatial pattern, change, drivers and impacts were proposed accordingly. To our knowledge, a synthesis review on the remote sensing and outlook on swidden agriculture has not been reported yet. This review paper aims to give a comprehensive overview of swidden agriculture studies in the domains of debated definition, trends, remote sensing methods and

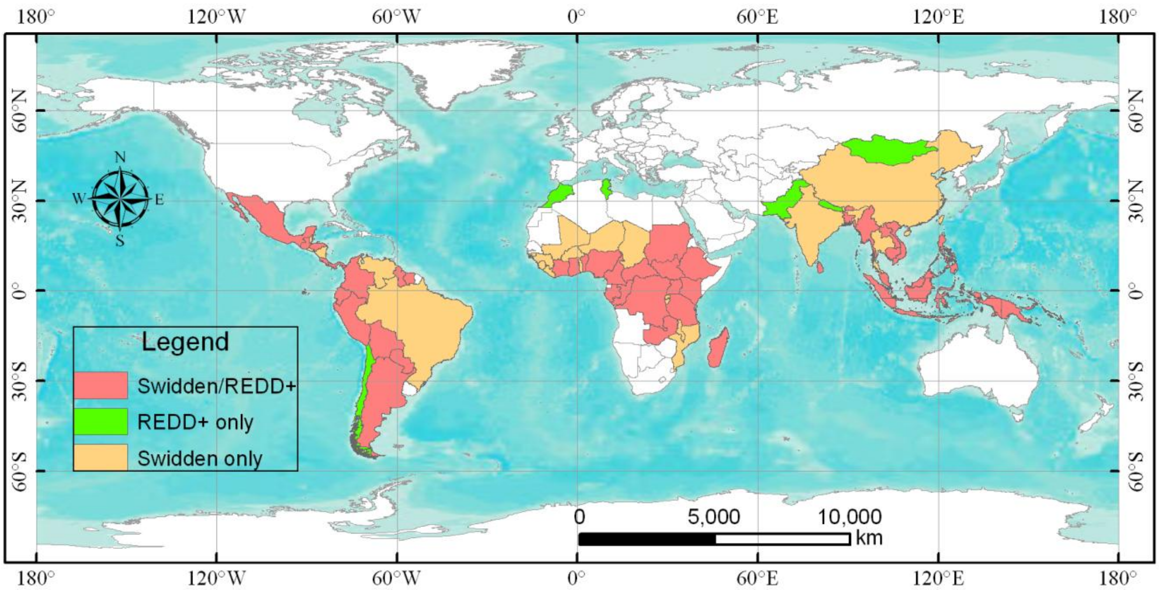
outlook research in SEA undertaken in the past two decades.

Keywords: swidden agriculture; remote sensing; fire-related; drivers; impacts; REDD; review; Southeast Asia (SEA)

1. Introduction

Swidden agriculture, also known as shifting cultivation or slash-and-burn farming, is an age-old and prevailing subsistence farming practice in the tropical regions [1–4]. There are 40–50 countries globally [5] with almost 300–500 million people directly or indirectly carrying out this traditional swiddening system [6–8]. Evidences from a recent meta-analysis published by van Vliet *et al.* [9] suggest that these swidden cultivators are mostly located in the mountainous and hilly parts of Latin America, Central Africa and Southeast Asia (SEA). Based on the Institute of Scientific Information (ISI) Web of Science database (8 October 2013), swidden agriculture is mainly practiced by smallholder farmers in a conservative estimate of 64 developing countries (Figure 1, [9–25]) from Africa, Latin America, and South/Southeast Asia. Forty-five of them are part of the United Nations collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (or the UN-REDD Programme) partner countries (currently 48 in total). It shows that the monitoring of swidden agriculture will greatly contribute to implementing and managing the REDD projects [10].

Figure 1. Spatial distribution of swidden practice (including shifting cultivation and slash-and-burn agriculture) in pan-tropical developing countries. Literature source: [9,11–25].



Swidden is perceived as the origin of current Asian agricultural systems [26]. The understanding of human being towards swidden agriculture started long before, if not synchronized with pioneer swidden cultivation. In a special issue published by the journal of *Agriculture, Ecosystems & Environment*, it reports that world pioneer analysis of slash-and-burn agriculture started earlier in the 1930s [7]. With respect to the studies of swidden cultivation in SEA, it can be traced back to the 1940s [27,28]. However, it is widely recognized that swidden cultivation began to gain close scrutiny in the 1950s from the social and natural sciences [29,30]. From the 1950s to 1960s, a number of important works on the land use practice were published by scientists predominantly from anthropology [31–34], and other disciplines including soil science [35], agronomy [36] and geography [37–39]. During the 1970s and 1980s, studies on swidden cultivation globally have expanded into many other fields, like the aspects of ecology and evolution [29,40], the sustainability under growing population [41], field experiments, swiddening technologies, swidden cropping system, labor, and the corresponding relationships with socio-economy, culture, and politics [42]. Swidden agriculture has gradually become the scientific debate focus of the development of agroforestry in the humid countries [43]. In the 1990s, many scholars preferred to underline that the disadvantages of swidden cultivation outweighed its advantages. They then put forward many alternatives for this unsustainable practice across the tropical regions [4,44]. However, swidden agriculture is still a dominant agricultural system in the tropics [9].

In the background of climate change, deforestation and forest degradation triggered by slash-and-burn farming practice have greatly impacted the carbon sink globally, and attracted much concern from international communities [10,45]. From the United Nations Framework Convention on Climate Change in 1992 to the Kyoto Protocol in 1997, the policies of inter-governmental organization have immensely promoted research on the relationships among swidden agriculture and forest degradation and global warming. Furthermore, from the Bali Road Map drawn up in 2007 through the Copenhagen Accord approved two years later, the United Nations firstly proposed the UN-REDD Programme (or REDD+ later). After the Durban Climate Change Conference in 2011 and the Doha World Climate Summit 2012, the UN-REDD+ program has provided invaluable support for humid countries across Africa, Asia-Pacific and Latin America and the Caribbean to implement the corresponding national REDD+ strategies. As reported by Mertz [5], REDD+ will significantly influence swidden cultivation in the future, either as a new challenge or a major opportunity. Since the implementation of REDD+, there has been more original research work involving swidden farming in SEA and worldwide. However, to our knowledge, there are few surveys of systematical evaluation for swidden agriculture in the literature.

As a traditional farming in the pan-tropical region, swidden farming has been experiencing a rapid conversion and replacement from primary forest to monoculture plantations in SEA [10], such as oil palm [46,47], rubber [48,49], timber products (e.g., eucalyptus [50,51] and teak [52]), and other cash crops (e.g., cassava and sugar). Nevertheless, slash-and-burn techniques are firstly used to prepare a plot of land (swidden) for plantation agriculture without any doubt. Currently, along with the noticeable environmental consequences related to plantation monoculture, large amounts of research work have turned to quantify the effects in the last two decades [53]. The understanding of the dynamics of traditional slash-and-burn land use practice is of significant importance and will surely contribute to better assessing the environmental and socioeconomic impacts of monoculture plantations. However, much information remains unknown about the exact distribution, scale, changing rate spatially and temporally, and its induced impacts on local farmers' livelihoods and effects on eco-environment [9,54].

There are a few published synthesis papers of swidden farming in SEA. For instance, Mertz *et al.* and Schmidt-Vogt *et al.* summarized the demography of swiddeners [12] and the extent of swidden [11] in a special issue (Volume 37, Issue 3) of the journal of *Human Ecology* in 2009. Padoch *et al.* [54] and

Ellen [30] discussed the persistence of swidden cultivation in the future. In Ellen's review paper, he gave an overview and commentary on recent research work of swidden cultivation from the aspects of concept definition, theoretical approaches, political and socio-cultural impacts and ecological sustainability [30]. However, so far no review paper has clearly summarized the persistence or demise, detecting and mapping techniques using remotely sensed data, and outlook of future research directions of swidden farming. In the review paper, we searched the Google Scholar with the following key words: swidden, swidden agriculture, swidden farming, swidden cultivation, swidden system, swidden practice, shifting cultivation and slash and burn. Only data published in peer reviewed journals (140), specialized books (four), reports (four), proceedings (three), Ph.D. dissertation (one) on this traditional farming system with a longitudinal way were selected. Among them, a total of 92 publications were analyzed in SEA, specifically, Laos, Vietnam, Thailand, Myanmar, Cambodia, Indonesia, Malaysia and Philippines. The rest of this paper is arranged as follows: debate on the definition of slash-and-burn agriculture, swidden farming, and shifting cultivation were discussed in Section 2; prevailing viewpoints towards the persistence or demise of swidden agriculture were summarized in Section 3; remote sensing techniques for swidden agriculture delineation and mapping were reviewed in Section 4; and future prior research fields of swidden agriculture in SEA were proposed in Section 5.

2. Debate on the Concept of Terminologies

So far, it seems to be that there are no widely accepted and applicable definitions on swidden cultivation, shifting cultivation and slash-and-burn agriculture in the scientific community [55]. Terminologies of swidden agriculture, shifting cultivation, slash-and-burn farming, and other jargons, like *jhum* in South Asia are commonly mixed up in the scientific literature [9,55,56]. A recent review paper by Rambo questioned the rationality of utilizing these terms synonymously [57]. It seems that there is especially much controversy between swidden agriculture and shifting cultivation [58]. The term of swidden was firstly proposed by the Swedish anthropologist K.G. Izikovitz in 1951 [41], in the sense of "burned clearing" or "burned plots" of woody vegetation [26,59]. However, it was not popularly applied within the scientific cycle as scholars deemed it as an old English phrase in the 1960s [60]. The term of shifting cultivation refers more broadly to agricultural activities where fields are cultivated for rice and others crops then left fallow [59,61]. It includes the entire system of swidden plots and fallow vegetation [61]. Inoue pointed out that shifting cultivation was often practiced by shifting or semi-nomadic people for impermanent fields, even with relative fixed settlements [58]. To distinguish the term swidden form shifting-field cultivation, H.C. Conklin defined swidden agriculture as any farming practices in which fields are burned and cropped for shorter periods (several years) than the follow-up fallow [31].

In fact, the terms have two major differences. First, swiddening is a way of life associated with cultural traditions (*i.e.*, cultural identity) while shifting cultivation is a technical description of land-use system that alternates cropping and fallows [26]. In SEA, swidden cultivation is normally practiced by the locally ethnic minority groups. These poor farmers rely on this subsistence to a great extent. Second, from a fire-related point of view, swidden agriculture as well slash-and-burn farming is more preferable than the term of shifting cultivation [30,58]. The term of swidden cultivation matches well with the farming system in SEA [30]. Shifting cultivation was regarded as fire-free and mulch-based systems generally in the Pacific Islands [55]. As for slash-and-burn agriculture, it has a wider coverage of tropical extensive farming systems with the exception of shifting of fields *in situ*. In another special issue (Volume 41, Issue 1) on swidden agriculture published by the *Human Ecology* journal in 2013, a relatively broad working definition of swidden cultivation in SEA and other parts of the world as well was provided as follows: "*Swidden cultivation is a land use system that employs a natural or improved fallow phase, which is longer that the cultivation phase of annual crops, sufficiently long to be dominated by woody vegetation, and cleared by means of fire*" [55,62]. This definition also highlighted the usage of fire as an indicator of swidden cultivation to distinguish from shifting cultivation. In summary, the term swidden agriculture is more appropriate for describing the farming system in SEA because it includes unique attributes such as cultural identity and fire relatedness. Traditional swidden agriculture comprises slashing and burning stages and the cropping period. Currently, the slashing and burning practice has stayed the same but the crops cultivated are in the process of transformation into cash crops.

3. Debate on the Persistence or Demise of Swidden Agriculture

In the last century, the debate and concern on the persistence or demise of swidden cultivation has never officially ceased amongst governments and academics [30]. Negative perceptions from governments towards swiddening in general in SEA have accelerated the demise of this traditional swidden system. As for the debate on swidden agriculture, a prevailing dichotomy concerns; on the one hand, the persistence of this farming practice due to biodiversity preservation [63,64], livelihoods dependence [65] and cultural identity [66]; on the other hand, the demise of swiddening due to large scale plantations [10], economic development [67] and continuing urbanization [62]. Information on the debate on whether swidden agriculture will change not only reflects the cognitive differences against it from different disciplines, but also implies that swidden agriculture is highly controversial and worthy of extensive research.

3.1. Viewpoint of Demise

Scholars who hold the argument that swidden cultivation is destined to disappear generally consider that this primitive and extensive farming practice is destructive and non-sustainable and should seek alternative agriculture. In the tropics, the traditional swiddening system involves the following stages: conversion (forest slashing/felling, sun/air drying and burning during the dry season), cropping (settling familial farming for several years), and fallow (vegetation regenerating and soil organic content rejuvenating) [63,68,69]. During the stages of conversion and cropping, human activities frequently trigger a series of eco-environmental concerns, such as forest degradation and deforestation [70,71], total mineral nutrient loss [72,73], soil biota communities decline [73,74], atmospheric pollutions [4] and heavy metal contamination [75]. The regeneration of secondary vegetation/forest in the various fallow periods was regarded as the future of the tropical forests [76–78]. Yet, the length of fallow period will be a key factor for vegetation restoration [79]. Recently, factors like population growth, market and forest conservation policies have gradually shorten the fallow length [63,69,80] and exerted huge impacts on the vegetation recovery, carbon sequestration and sustainability of the forest ecosystem [3]. Towards these negative effects of swidden agriculture, governments and scientific communities have always attempted to eradicate the age-old farming practice and seek alternative agriculture systems [3,81,82]. In 1996, *Agriculture, Ecosystems & Environment* published a special issue (Volume 58, Issue 1) on "Alternatives to Slash-and-Burn Agriculture" in the world [7]. Padoch *et al.* assessed the possible demise of swidden agriculture in SEA and confirmed that swidden cultivation is disappearing in many parts of mainland Southeast Asia (MSEA) [54]. Much the same conclusion is reported in a case study in a remote upland village in north central Vietnam, in which swidden agricultural practices were reduced substantially due to government restrictions [83].

Besides, economic, cultural, ecological and political factors would also cause the decline or disappearing of swidden agriculture worldwide [62], such as the access to market, distance to major roads, off-farm job opportunity, ethnic minorities and land policies. In a meta-analysis of global assessment on the trends and drivers of changes in swiddening, it states that the access to markets and conservation policies and practices have exacerbated the decline of swidden agriculture [9]. Evidence from northwestern Vietnam [84] underlines that accessibility or distance of ethnic groups to major roads will influence their attitude towards subsistence agriculture. Local residents living close to major roads tend to develop market-oriented farming practices to improve their income sources, while those who residing in remote mountainous areas are forced to rely on swidden cultivation. Intensive plantations will be another emerging driver of the rapid land transformation of swidden fields and fallows on slopes to other diversified farming systems, like rubber plantations in MSEA [48] and oil palm plantations in insular Southeast Asia (ISEA) [46].

3.2. Viewpoint of Persistence

Swiddening system is a centuries-old and dynamic land use type. Swidden decreased in many mountainous areas of SEA. It is widely considered that this practice will be replaced by other intensive farming systems. However, scientists contend that it is inopportune to claim that swidden cultivation comes to an end [85]. Conversely, it still persists in many parts [30,54]. Fox *et al.* concluded that swidden agriculture is still a predominant land use form in this region in the past half century based on a summarization of eight locale studies in montane MSEA [86]. Coincidentally, van Vliet *et al.* insisted that swiddening system will continue to exist and thrive in many areas of the Earth based on a global meta-analysis, in spite of a visible decrement of swidden cultivation in global tropical forest-agriculture frontiers [9]. van Vliet *et al.* acknowledged the decline and transformation of swidden farming practice in the special issue (Volume 41, Issue 1, 2013) of *Human Ecology* on swidden agriculture, however, he also emphasized that swidden agriculture is likely to persist for some time into the 21st century and it is hard to predict a time frame for swidden demise based on the analysis provided in this special issue [60]. For example, in Palawan Island of the Philippines, although driven by the state's laws, policies, and practices to curb swidden cultivation, local farmers argue that swidden is still a *de facto* vital and integral practice [85]. What is more, the implementation of government agrarian policies to substitute swidden agriculture sometimes causes negative effects on the livelihoods of local residents [83] and brings unsustainable development [87]. Farmers in some locations have returned to undertake swidden cultivation after decades. A case in point is in the Sarawak, Malaysia [67,88,89]. One viewpoint is that the growing reliance on forest products and services from swidden fields and secondary forest fallows sustains swidden agriculture [54]. The fundamental reason is poverty. Maintaining swidden cultivation helps local farmers to alleviate the impact due to commodity price fluctuations [90]. These people usually dwell in relatively inaccessible mountainous and hilly parts, and partially or fully, directly or indirectly, have to turn to swidden cultivation for subsistence [91]. Cramb *et al.* highlighted that swidden farming plays a key role in ensuring the livelihood safety of local cultivators against market fluctuations in SEA [65]. An empirical research [92] carried out in Vietnam's uplands accentuated that traditional composite swidden agriculture was perceived as an environment-friendly and sustainable farming system to improve household grain production.

In opposition to the negative attitude towards swidden farming, other scholars advocated that those one-sided perceptions need to be altered [93]. They began to question and reconsider the prevalent perceptions on the effects of swidden cultivation. Several case studies in northern Thailand were adduced to exemplify the probability of conserving biodiversity under well-maintained swidden farming [94]. Fox considered that swidden agriculture is ecologically appropriate, culturally suitable, and the effective way to conserve biological diversity in SEA [63]. This is especially appropriate in the upland regions of MSEA for their dietary preference for rice, smallholder subsistence, and the incapacity to bring in tillage technology on sloping lands [95]. Many other studies also elaborated the economic and environmental rationality of swidden agriculture in the humid and mountainous context. By means of case study in West Kalimantan of Indonesia, de Jong recognized that swidden agriculture systems not only stimulate regional economic development, but also contribute to maintaining biodiversity [93].

To sum up, in SEA, earlier studies especially published in the 1990s normally claimed that swidden agriculture would come to an end as they provided a great deal of evidence of environmental consequences. However, recent studies reported in the last decade emphasized the positive effects of swidden farming on the local livelihoods and biodiversity. In fact, under the promotion of regional economic integration since 1992, road connectivity and market accessibility have accelerated the transition of traditional swidden farming into market-oriented agriculture. It leads to the unavoidable disappearance of swidden agriculture, especially in the uplands, first and foremost influenced by the improvement of infrastructure. However, SEA is still a less developed region, particularly the countries in MSEA, like Myanmar, Laos and Cambodia. The MSEA has a vast area of mountains and plateaus which are home to many ethnic groups. The lagging socio-economic development remains a noteworthy factor for continuously maintaining and relying on swidden agriculture. Therefore, the dominant farming system will exist in many mountainous parts of SEA as in the past but are facing drastic transitions to some degree. Related research of the transitions, such as how swidden agriculture changes, to what extent, the driving forces and potential impacts deserve further analysis.

4. Remote Sensing Techniques for Detecting and Mapping Swidden Cultivation

Previous studies of swidden cultivation fall into three broad research areas from the viewpoints of analyzing scales and involved subjects: microscopic observational studies of anthropology or ethnology, meso- and macroscopic comparative studies of geography, and experimental studies of natural science and agronomy [58]. Both observational and experimental studies have a long history, with studies dating back to the 1950s and 1960s in the fields of anthropology [31,32,34], soil science [35] and agronomics [36]. The methods used in these earlier studies are primarily empirical studies [58]. By contrast, numerous earlier geographical studies of swidden agriculture were descriptive due to the constraints of monitoring techniques and data over macroscopic scale [58].

Since 1970s, remote sensing techniques have provided persistent impetus to environmental changes monitoring. Swidden agriculture (or slash-and-burn practice) is widely perceived as one of the primary causes for deforestation throughout the pan-tropical regions [96]. Because of the diverse, complex and dynamic features of swidden system, so far, accurate assessment with remote sensing imagery is very challenging [11,54,97] due mainly to difficulties in detecting swidden practice with remote sensing methods [62]. Therefore, the thematic maps and statistical data on swidden cultivation at regional or national scale were relatively lacking [97], which severely constrained our understanding of the impacts on environment consequences and local swiddeners' livelihoods owing to the rapid changes in swidden farming. Both the intrinsic characteristics of being an agroforestry system and extrinsic negative conception limited extensive investigations of swidden agriculture with remote sensing techniques [97,98].

However, remote sensing data can provide valuable information on fire events and burned area due to its synoptic, multi-temporal, multi-spectral and repetitive coverage capabilities [99]. In contrary, studies of detecting burnt area or fire scar or wildland fire with satellite imagery were widely reported. For example, Mallinis *et al.* compared 10 methods for mapping burned area in a Mediterranean setting using Landsat Thematic Mapper (TM) imagery [100], including spectral unmixing, artificial neutral networks (ANN), logistic regression, maximum likelihood, thresholding of spectral vegetation indices, hue-lightness-saturation (HIS) transformation, principal component analysis, classification and regression trees, object-based image analysis and support vector machines (SVM). It is worthwhile to note that the common feature between intentional burning for clearing lands and unintentional forest wildfire is fire-related [101,102]. Burning is an important phase for swidden agriculture. This fact highlights that the methodology for detecting fire condition, burned area and swidden practice would be very similar. One convincing case study is from Müller and his coauthors, which applied Moderate Resolution Imaging Spectroradiometer (MODIS) active fire data to detect swidden-induced fires in Laos [101].

This section is arranged as follows: first, briefly comparing the advantages and disadvantages of commonly used satellite data for monitoring swidden agriculture, and then reviewing the main categorized approaches for mapping swidden agriculture involving spectral signature, phenology characteristics, statistical theory and landscape ecology.

4.1. Satellite Data for Operational Swidden Agriculture Monitoring

Various sources of satellite imagery have been provided for monitoring the biophysical changes on the Earth's surface in the last decades, including optical and radar remote sensing data. In this part, an overview of satellite data that can be used for delineating swidden cultivation was presented. They are medium spatial resolution imagery represented by Landsat family series, coarse spatial resolution imagery by MODIS and Synthetic Aperture Radar (SAR) data.

Of the various satellite sensors used in fire-related studies, Landsat imagery may probably be the most commonly used [103]. Several factors can explain the extensive investigations with Landsat TM, Enhanced Thematic Mapper plus (ETM+) and Operational Land Imager (OLI) data, including a long consistent acquisition record (nearly three decades), a medium spatial resolution (30 m for the optical bands) appropriate for the identification swidden (or burned plots) at the pixel level, a combination of visible, near infrared (NIR), and short-wave infrared (SWIR) bands, and free availability via the Internet since 2008. Therefore, Landsat TM, ETM+ and OLI data are particularly suitable for mapping burned area [104]. However, swidden landscapes were generally considered difficult to map in the past in SEA because of the complex and dynamic feature of swidden farming [54]. Recently, scholars start to tackle these difficulties head-on. For example, Hansen and Mertz quantified the change in swidden cultivation in Sarawak of Malaysia with a supervised Maximum Likelihood Classification method [89]. Leisz *et al.* identified and mapped swidden farming system with Landsat imagery in Vietnam's northern mountain region [105]. Years later, he further validated that Landsat data held great potential for accurately detecting swidden/fallow using a rule-based non-parametric hybrid classification method in Vietnam's north-central mountains [106]. Nevertheless, Landsat imagery is still extremely underutilized in delineating swidden farming especially in a case of free Landsat data distribution policy. It is customarily deemed that cloud problem is an inconvenient fact for swidden detection with Landsat data as it belongs to a tropical farming system. Actually, swidden practices (*i.e.*, slashing, drying, and burning) are normally implemented in the dry season when the Landsat satellites usually gather high-quality imagery [107]. So far, Landsat-related methods for swidden detecting are less reported. Similarly, this is the same case for swidden cultivation monitoring with other Landsat-like optical data.

Another data option for mapping swidden cultivation in upland areas of SEA goes to MODIS data. Differing from Landsat data products, MODIS data highlights the time-series analysis at eight to 16 days. MODIS data products overcome the cloud issue to some extent with the compositing techniques. Consistently, swidden agriculture is characterized by several consecutive temporal stages. For example, Xiao *et al.* delineated the recovery of vegetation canopy after severe fire with MODIS-based time-series vegetation indices [108]. Hurri *et al.* used MODIS time-series Enhanced Vegetation Index (EVI) data to classify swidden cultivation landscapes in northern Laos in combination with landscape metrics [97]. By contrast, MODIS fire products and SPOT VEGETATION data are widely utilized in the fields of burned area and fire detection. Until now, direct applications in monitoring swidden farming systems with coarse spatial resolution data are far less reported. This difference may have a close relationship with the size and extent of burning areas *in situ*. Wildland fire easily causes vast area of biomass destruction while burning in swidden practice is controllable, usually within a limited space. Coarse resolution data easily leads to classification errors.

Besides, Synthetic Aperture Radar (SAR) data also has unique capabilities for fire scars and burnt area monitoring because microwave energy can penetrate clouds [109,110]. This feature is particularly critical for mapping fire scars in tropical forest. During the dry season, local swiddeners prepare a great number of burned plots (swidden) for food and cash crops planting in SEA. SAR data may also be an alternative data source for swidden mapping. In addition, SAR data (e.g., European Remote Sensing Satellite and Radarsat) usually has finer spatial resolution suitable for regional swidden transition monitoring. To our knowledge, swidden cultivation mapping using SAR data is seldom reported. The possible factors may attribute to the limited access to the SAR data and negative attitude towards swidden agriculture.

Based on the comparisons of three categorized satellite data, considering the data availability and feasibility, we believe that the Landsat historical multi-decadal images are the most appropriate and consistent satellite data for swidden agriculture monitoring. It is anticipated that there will be increasingly more studies under the promotion of the REDD program.

4.2. Spectral Signatures Based Approaches

Spectral signatures based approaches mainly highlight the differences of the burned and unburned pixels or pre/post-burn pixels. The variability of spectral signatures of burned area depends on the vegetation types that burn [111,112]. For example, the NIR reflectance decreases significantly due to the destruction of leaf cells within vegetation for all the types of vegetation [100,112–114]. However, the reflectance of visible and SWIR spectral channels of forests and woodlands may increase [113], or decrease [112], and decrease for grasslands and croplands [112]. Mallinis *et al.* found that mid-infrared band (or Landsat-5/7/8 band 7, SWIR 2) shows significant increase due to the reduction in canopy moisture and shadow [100]. Therefore, these linear variations in chlorophyll content, vegetation cover, moisture content and soil composition can be detected and monitored by spectral vegetation indices derived from satellite images, including the Global Environmental Monitoring Index (GEMI) [115], Burned Area Index (BAI) [116], Normalized Difference Vegetation Index (NDVI) [117], the Soil-Adjusted Vegetation Index (SAVI) [118], the Enhanced Vegetation Index (EVI) [97], the Land Surface Water Index (LSWI) [108], and the Normalized Burn Ratio (NBR) [118], *etcetera*.

The foregoing vegetation indices can be divided into two categories based on the spectral bands used: NIR (0.7–1.2 μm) and Visible (VIS, 0.4–0.7 μm); NIR and SWIR (SWIR 1: 1.5–1.8 μm and SWIR 2: 2.0–2.4 μm). As a number of previously or currently optional sensors (like Landsat MSS, SPOT-1/2/3, IRS WiFS, and HJ A/B) only consist of NIR and visible bands, the NIR-Red range is critical for mapping historical burned areas [116]. In this case, NDVI is often used to extract burnt patches in the NIR-Red spectral domain. However, it is proved that NDVI is less effective than BAI and GEMI [116,119]. By contrast, the accessibility of SWIR bands has demonstrated better performance in discriminating between burned and unburned surfaces [116]. Nevertheless, only a few satellite sensors (Landsat TM/ETM+, ASTER, and MODIS) cover the SWIR bands, specially the SWIR 2 [120]. Among them, NBR, calculated with NIR and SWIR 2, is a most effective index for mapping burned area of closed-canopy forest and is most reported in vast literature [113,118].

The methodology mainly encompasses two types: one is to use threshold approach with single post-burn image; the other is to apply difference approach with bi-temporal images, corresponding to the pre- and post-burn acquisition, respectively [121]. The single-date method is to discriminate the burned from the unburned for the same scene, while the bi-temporal method is to delineate land cover changes for burned ground objects. With regard to the performance of the two types, each airs his own views. Scholars who hold that single post-burn methods outperform bi-temporal ones highlight not only the operability and low demand on data acquisition, but also the avoidance of mis-registration of radiometric and geometric correction [121]. In contrary, there are those who argue that the usage of bi-temporal images was proved to provide more accurate classification results by eliminating subjective judgments. Currently, the foregoing methods are widely used in the post-fire burn measurement due to wildland fire, covering burned area mapping and burn severity evaluation.

Spectral signatures are the fundamental features of remote sensing. Other related methods for swidden agriculture discrimination also include supervised/unsupervised classification, decision tree classifier, image enhancement involving band ratios, and object-based image analysis. Take the image enhancement technique for example; multispectral satellites (e.g., Landsat) provide various band ratios to display enhanced images in red, green, blue or false color composite and highlight the land cover differences [122,123].

4.3. Phenological Features Based Approaches

During the dry season in SEA, swidden farming accompanies seasonal changes in land cover types which are amenable to remote sensing monitoring. These changes involve well-grown woody vegetation, felling/slashing, sun/air drying and burning. The slash-and-burn practices consume vegetation, destroy leaf chlorophyll, expose soils and alter aboveground and belowground moisture content [111,114,118]. Among them, artificial burning in swidden cultivation usually leads to the most drastic morphological and physiological changes. Morphological response is commonly seen in post-fire landscapes, manifested through changes in vegetation shape and ground surface color and component. Physiological response is demonstrated through decreased plant photosynthetic pigments and moisture content. After a fire, spatial morphological effect is very noticeable for burned area mapping. While individual physiological adjustment differs extensively due to the combustion process and duration. Thus, burn severity mapping also gains much attention across the wildland fire community [124].

Therefore, swidden practices can also be monitored using time-series vegetation indices (NDVI, LSWI and NBR) derived from Landsat-family sensors in SEA. Time-series image analysis is often conducted with high temporal resolution images such as MODIS, SPOT/VGT and NOAA/AVHRR, however, it is not suitable for swidden agriculture mapping there due to the coarse spatial resolution. This region has a tropical monsoon climate. It encompasses three distinct seasons, *i.e.*, the hot season (March–April), rainy season (May–October), and cool and dry season (November–February) [125]. During the dry season (November–April), the light cloudy weather makes the acquisitions of cloud-free imagery possible for time-series analysis. For example, statistics from the USGS GloVis showed that there are 28 ETM+ or OLI scenes (Worldwide Reference System (WRS)-2 path/row = 130/046) with cloud coverage less than or equal to 10% during 2009–2013. Among them, 25 scenes were acquired from November to April, while only three scenes were available between May and October [107]. Swidden practice consists of several key phenological stages. According to our field survey in 2013 and primary analysis, it starts felling or slashing in February, drying by sun/air in March, and burning in April, the end of dry season with the highest temperatures each year. The significant changes in vegetation and soil moisture can be detected by spectral vegetation indices during these time windows. Currently, the Landsat family satellites (Landsat-7/8) with an eight-day repetitive coverage and the China Environment Satellites HJ-1A/B with a four-day temporal resolution may facilitate such time-series analysis. To our knowledge, studies of using Landsat-like sensors data to accurately detect swidden agriculture through time-series image analysis in SEA is still very few, however, there will be more as many satellites' imagery becomes freely accessible.

4.4. Statistical Theory Based Approaches

Logistic regression model belongs to linear regression and is a commonly applied machine learning method. It was originally developed for survival analysis and presently is extensively used in natural and social science fields. This statistical multivariate technique consists of two major categories: binomial (or binary) and multinomial, which coincide with two post-fire burn measurements, that is burned area mapping and burn severity mapping [100,114]. Binomial logistic regression involves the situation of occurrences in a dichotomous manner, for instance, burned or unburned [112,113,121]. Multinomial logistic regression involves the circumstance in which the results can comprise three or more possible types, like unburned, light burn, moderate burn, and severe burn [126].

Currently, burned surfaces predicting or mapping through the logistic regression model is more reported than burn severity mapping. In contrast, the multinomial logistic regression model has not been used extensively for fire severity mapping. It is probably because binomial logistic regression is more feasible than multinomial logistic regression. As for monitoring fire-related events, the combined use of remote sensing technique and logistic regression model makes the burned area mapping a simple and straightforward question. It only determinates the attribute of burned or unburned for a candidate pixel according to an indicator, like the probabilities of presence and absence [121,127]. The set of independent variables usually comprises radiometric or reflectance values of spectral channels and derivative vegetation indices. The outcome is normally quantified for a burned pixel or not based on the dummy or indicator. Therefore, logistic regression model is a flexible and effective statistical method for mapping burned area not only at regional scale [120] but also over larger spatial scales with global coverage satellite imagery (e.g., NOAA/AVHRR, SPOT/VGT and MODIS) [128,129]. In addition, logistic regression techniques are also applied to predict the probability of wildland fires in combination with geographic datasets. For example, de Vasconcelos *et al.* used logistic regression model to spatially predict ignition probabilities of wildland fires in central Portugal [130]. Alencar *et al.* applied logistic regression techniques to estimate the probability of forest understory fire in an eastern Amazonian landscape [131]. All in all, as the burning is the common trait between wildland fire and swidden farming, our hypothesis is that the aforementioned techniques may contribute to the detecting and mapping for swidden cultivation practice in the mountainous area of SEA.

Other statistical based approaches with remote sensing comprise ANN and SVM. ANN belongs to artificial intelligence techniques and has received much focus on the fire-related monitoring of remotely sensed data [132,133]. In comparison with traditional classifiers, ANN has advantages in distribution-free of data, compatibility of data and input structures, requirement of less training data, and attenuation of non-linear data patterns [132,133]. Currently, a feed-forward multi-layer perception ANN with back-propagation algorithm is often applied [100,127]. Comparative analysis between ANN and logistic regression in predicting spatially distributed probabilities of wildland forest ignition or burnt scars produced acceptable classification accuracy, yet with an opposite conclusion which performed better [127,130]. Mallinis and Koutsias found that ANN showed better accuracy and robustness in mapping burned area of three study sites in Greece over nine other classifiers [100]. Presently, both optical (e.g., NOAA/AVHRR and Landsat) and Radar satellite images (e.g., RADARSAT products) have been applied in burned area identification with ANN [110,127,132].

SVM belongs to linear classifiers and has also gained popularity in the burned area identification with satellite imagery in the last decade. Compared with conventional classification methods, SVM has several advantages in the following aspects [104,134]: (i) dealing with learning problems with a limited number of training sets; (ii) overcoming the pre-determination of optimal threshold; (iii) and dealing with high dimensionality datasets. Especially, the avoidance of setting a critical threshold is undoubtedly a notable improvement in mapping burned area with single-date image. For example, Cao *et al.* used daily MODIS data to map burn scar using an automatic region growing method based on SVM [134]. Petropoulos *et al.* investigated the potential of combined use of SVM classifier with Landsat TM imagery for delineating burnt area in a Mediterranean setting [104]. Both ANN and SVM are supervised classifiers which classified different land cover types based on training sets. However, these methods are seldom reported in the literatures of swidden agriculture detecting and mapping. With these methods, it will be applicable to monitor the spatio-temporal pattern and transition pace of this dominant tradition farming.

4.5. Landscape Ecology Based Approaches

In view of the annual dynamic and rotational nature of swidden practice, detecting and monitoring the spatio-temporal patterns of swidden farming is challenged for many aspects [97,135].To begin with, the different swidden-fallow cycles may lead to multiple interpretations of land use classification as there are no explicit boundaries between swidden cultivation and other types of land use and land cover. Additionally, the fragmentation of swidden patches in the backdrop of vast forest landscape also makes the updated mapping at pixel level a very hard task [136]. Therefore, scholars attempt to delineate swidden system using Landscape Ecology methods at the landscape scale. Normally, the landscape mosaics approach and landscape metrics approach are regularly used in swidden mapping with remote sensing data [97,136–138].

The landscape mosaic approach only focuses on the spatial compositions of land cover patches across the territory (*i.e.*, land cover mosaics), and leaves alone the specific information of land use types [137]. The basic idea of this approach is that the overall landscape composition in an area with a stable swidden system remains unchanged, despite the spatio-temporal land cover changes related to swidden [136]. Landscape mosaics approach consists of two steps [137]. The first step is to analyze spatial pattern of various land cover types rather than the corresponding land use types. The second step is to interpret the landscape mosaics based on the land cover mosaics within a socio-political context.

Currently, two related research studies were conducted at the local to national scale in Laos using the landscape mosaics approach [136,137]. The groundbreaking method was firstly reported in a study of Messerli *et al.* [137]. Unlike the pure remote sensing classifiers, this approach treats swidden system as a whole. It emphasizes the land cover change of swidden system instead of a given temporal phase. The landscape of swidden differs greatly from forest and other land cover landscape. With a land cover map in 2002, the authors delineated the spatial pattern of swidden farming and other types of landscapes by using a moving window technique [137]. Analogously, Hett *et al.* spatially identified swidden system using land cover data in 2009 from a REDD+ perspective [136]. This approach holds great potential for mapping swidden cultivation landscapes, yet it normally relies on existing land cover inventories [97]. Therefore, it may reduce the credibility and timeliness of results in the following aspects. First, it delineated the swidden landscape at the meso-level but not the specific spatial information of it at the micro-level. It is a big step forward in comparison to qualitative analysis by Schmidt-Vogt *et al.* [11]. Second, as land cover inventories are often derived within a period of multiple years, the unique feature of swidden practice that changes rapidly year by year will not be able to reveal its spatial changing information. There is seldom information on swidden cultivation on land use maps due to negative attitude from governments towards this traditional farming practice [54].

In view of aforementioned shortcomings, the landscape metrics approach was subsequently proposed to detect and monitor swidden cultivation dominated landscapes by combining moving window techniques in northern Laos [97,138]. This method makes the dynamic monitoring of swidden cultivation possible with either single land cover dataset or time-series satellite imagery. It greatly overcomes the difficulties in delineating this dynamic and complex practice with remotely sensed techniques. This approach mainly consists of two parts, namely, land cover classification with satellite imagery and swidden cultivation delineation with landscape metrics. The development of landscape metrics is also based on the landscape mosaics theory. In MSEA, swidden practice patches are randomly distributed with other types of land use and land cover landscapes. Therefore, the selection of landscape metrics for detecting swidden landscape needs to be closely related to its landscape process and pattern [138]. For example, Hurni *et al.* applied two spatial statistical indicators, namely the area proportion of all change land cover classes and variation coefficient of the area for changed land cover classes [97]. Then, the swidden cultivation dominated landscape was identified with a high area share of change classes and a low variation coefficient. In a recent study of Hurni *et al.* [138], they utilized three landscape metrics for deriving the swidden cultivation landscape and two landscape metrics for deriving the agriculturally unused forest patches. Nevertheless, landscape metrics approach has shown the potential for evaluating swidden cultivation landscape, yet it is still a new attempt toward the spatial mapping of swidden systems. More attention should be paid to the definition of broad land cover classes and the selection of landscape metrics when applying this approach in other swidden dominated regions.

5. Outlook on Future Research of Swidden Agriculture

Many studies show that swidden cultivation will continue to be treated as a dominant land use type in mountainous MSEA in the 21st century [54,62], although it has started declining and transforming into other land use types. The underlying causes can be summarized into two aspects. One is the continuing reliance on swidden farming of the poor in many frontier regions [65]. Ordinarily, swidden cultivation is mainly practiced by the ethnic minority groups settled in inaccessible uplands [139]. The other is the need to enhance the ecosystem services of biological diversity preservation [64,140]. It thus raises a series of questions which need further in-depth research for swidden agricultural systems. Five major aspects were summarized in this synthesis paper: (1) developing more remote sensing techniques for swidden farming; (2) delineating the spatial extent and dynamics of swidden agriculture systems; (3) understanding the transformation pace and trend of swidden practice; (4) investigating the underlying drivers of the change of swidden agriculture; and (5) evaluating the socio-economic and eco-environment impacts due to the transformation of swidden systems.

5.1. Developing More Remote Sensing Techniques for Swidden Agriculture

As swidden cultivation becomes the research focus in the fields of agroforestry ecosystem management and climate change, an increasing number of web-enabled satellite images will facilitate comprehensive understanding of the spatial pattern and temporal change process. In the past, swidden cultivation, as a dominant land use type, was often classified as unused or abandoned categories in remote sensing classification [11]. However, the historical footprint data were extremely underutilized and very few research studies have so far explored the remote sensing techniques for swidden identification and mapping. Literature shows that a diverse number of remotely sensed algorithms or models have been applied in the fields of fire ignition probabilities, burnt area and burn severity in the boreal forest region and Mediterranean climate zone [104,109]. By contrast, swidden-related burned area mapping techniques used in the subtropical and tropical regions were not adequately investigated. The lagging development of methodologies for swidden monitoring and mapping greatly limits our knowledge towards the swidden in the remote mountainous regions, let alone evaluating their socio-economic and environmental impacts.

For these reasons, first, those remote sensing techniques used for delineating burnt area and fire ignition probabilities can be introduced to swidden agriculture due to the common feature of the burning phase with a fire. The uni-temporal or multi-temporal methods can be adapted to track the changes in vegetation and moisture with satellite imagery acquired before and/or after burning in the dry season. More research works are awaited to investigate the potential of commonly used vegetation indices (such as NDVI, LSWI, and NBR), ANN and SVM in the swidden domain. Second, as swidden agriculture has noticeable phenological and physiological characteristics, covering sound woody vegetation, felling/slashing, sun/air drying, burning, cropping and long fallow period, it is expected that more phenology-based algorithms could be developed in the future. In particular, more emphasis should be put on the dry season in which the felling/slashing and burning phases are concentrated in a certain period and cloud-free images are easily collected. In other words, in comparison to rainy season, dry season could be the optimal temporal window for mapping swidden with remote sensing data. The designing of suitable swidden mapping techniques will treat swidden agriculture as an independent land use type.

5.2. Monitoring the Spatial Extent and Dynamics of Swidden Agriculture

As a prominent land use practice in montane SEA, the geographical knowledge of swidden agriculture systems remains extremely scarce [11], although a few sporadic regional research works on spatial delineation have been reported recently. At this stage, the academia and government departments are only aware that swidden agricultural systems still exist in certain regions within some countries [5]. However, with respect to the precise location and extent of the occurrence of swidden practice, and the transformation speed and scale to other land use types, the related information is scanty [54]. Thus, the understanding of swidden remains at a very low level. In addition, another aspect that limits our knowledge of swidden is the accurate population involved in swidden farming. Generally, most swiddeners are economically backward ethnic minorities that settle in remote mountainous areas with poor accessibility. The lack of updated swidden agriculture maps is not only a key stumbling block for explicitly revealing the distribution of swiddeners, but also leads to much difficulty in improving their livelihood due to the knowledge gap, let alone to assess the swidden-induced eco-environmental impacts [11,12].

In comparison to other common types of land use and land cover in montane SEA, in the case of much existing remote sensing data, basic research work toward swidden systems is far from reaching the requirements of decision-making. It should be noted that an increasing number of peer-reviewed literatures concentrate their focus on forests classification, likely natural forests against tree plantations (e.g., rubber and oil palm) in SEA. The continuous demands of commercial tree plantations have stipulated rapid transition from natural or secondary forests to tree cash crops or permanent agriculture. However, in contrast, the swidden agriculture system is seldom fully considered as a separate land use type in the foregoing studies. As an intermediate process of land use and land cover change, swidden practice is often neglected for two major reasons, namely the natural environment features of swidden agriculture and the inaccessible satellite imagery in the past. It limits our understanding of spatial distribution and dynamics at the regional to national scale from a geographical perspective.

Nowadays, scientists are seeking to detect and monitor the spatiotemporal pattern and dynamics of swidden agriculture using remote sensing data [11]. Fortunately, a number of high quality and free available satellite data facilitate the ongoing research work, such as Landsat and MODIS, to name a few. The historical archive of Landsat data can be used to assess the trajectory of swidden agriculture systems at regional level over 40 years; while MODIS time series data can also be used at the national level for the last decade. However, both sensors have advantages and disadvantages in spatial, temporal and spectral resolution for detecting and monitoring swidden cultivation. For example, Landsat imagery has greater potential for identifying small patches of swidden fields (0.5–2.0 ha) [141] with finer spatial resolution (30 m) and delineating swidden system change trajectory due to longer image acquisition history. MODIS imagery offers promise for describing the temporal dynamics of swidden cultivation at a finer temporal level. In combination with the merits of both sensors, Hurni *et al.* delineated the swidden cultivation landscape in northern Laos with landscape metrics and moving window techniques [97]. Nevertheless, in essence, the swidden cultivation landscape obtained by Hurni and his colleagues still does not answer the specific question about where swidden practice occurs, instead of providing an idea of the approximate extent of the swidden landscape.

5.3. Understanding How Swidden Agricultural Changes

A number of recent studies have pointed out that swidden agriculture has transformed or is in the process of rapid conversion into other land use types in SEA [9]. However, there is a knowledge gap on how this transformation happens in specific regions due to internal and external factors, like the market economy and land use policies. To begin with, much is uncertain about how much and how fast the swidden system will change into tree plantations, cash crops and permanent agriculture [54]. For example, rubber plantations will enhance the persistence and development of swidden practice, especially the slashing and burning practices [141]. In addition, there is also a lack of information on the fallow cycle, cropping intensity, and fallow vegetation recovery when the traditional techniques of swidden are maintained under the impacts of population growth and climate change. It should be noted that the academic focus is centered on the recent rapid transition and its environmental effects. On the contrary, related studies on how swidden keeps its traditional form are not often reported. Based on the current research progress, it is very difficult to make a final conclusion whether swidden practice will continuously persist or demise in an assumed schedule.

More importantly, research on swidden agricultural systems change is at a crossroads [136]. As a dominant agricultural system on sloping forested lands in SEA, swiddening continually provides necessary subsistence products for local remote farmers. This man-land relationship has been stably maintained for ages. Meanwhile, swidden farming has also played key roles in preserving ecosystem services and cultural identity [66]. In the last two decades, with the rapid economic development and deepening trade and investment collaboration, especially since the launch of the Greater Mekong Sub-regional (GMS) Economic Cooperation Program in 1992, swidden agriculture is confronted with noticeable transformation into other land use types due to the expanding infrastructure networks and accessible market opportunities [137]. It is noteworthy that easier and frequent involvement in a market economy might increase the risk. For example, market factors like commodity prices fluctuations will allow a shift between swidden cultivation and cash cropping [90]. Thus, swidden practice can be an effective strategy to cope with market fluctuation [65,90]. However, the REDD+ action program will pose a profound effect on the development of swidden system, such as government's curtailment. Yet, the impacts on the swidden system from this mechanism have two sides, both a challenge and opportunity [5]. For instance, Ziegler *et al.* claimed that swidden system should be maintained and assured with fallow periods for secondary forest regeneration in the case of global climate change debate [66]. The future change of swidden agricultural system is determined by multiple factors. Nevertheless, much is undefined about how the swidden system will change in this century.

5.4. Analyzing the Underlying Drivers of Swidden Agriculture Changes

Swidden practice has been prevailing in the mountainous regions of SEA for many centuries, yet it has begun rapid and extensive transitions to other land use types since the 1990s [98]. Before that, wars and conflicts greatly hindered the economic development of many countries in SEA. The GMS Program started in 1992 increased the opportunities for economic cooperation between/among these countries. Economic opportunities drive land use and land cover changes in the world [142]. As a disputable land use type in SEA, the expansion or reduction of swidden cultivation is influenced by many factors (e.g., policies and market) [97]. Currently, much is unknown about the driving forces for the transformation of the swidden agricultural system in many member countries of the Association of Southeast Asian Nations (ASEAN). In fact, the big differences in socio-political systems, economic development, land tenure systems, cultures and religions among these countries make the driving factors become complex and diverse. It is therefore necessary to investigate the underlying socio-economic and biophysical factors of swidden agriculture changes [9,97]. To better understand how different factors affect swidden cultivation, spatially explicit assessment should be one of directions for future research [97]. More details of the different factors affecting swidden agriculture will not only shed light on the debate over the persistence or demise of swidden [98], but also help in better understanding the livelihood impacts on swiddeners [65,90] and environmental effects on forest ecosystems and biodiversity as well [64,66].

A few exploratory qualitative analyses on driving forces of swidden system change have been carried out based on the sporadic studies in some countries. Fox *et al.* summarized six main factors for the transformation of swidden system according to six case studies in SEA. The factors comprise labeling swiddeners as ethnic minorities, under-realizing swidden as an agroforestry system, encroachments on swidden by forests development, resettlement, land privatization and commoditization and, expansion of market infrastructure and commercial agriculture [98]. Evidences from swidden agriculture in Palawan Island of Philippines suggest that government policies and laws reinforce its decline, yet local farmers still lean on it because of the livelihood risk [85,143]. Additionally, Robichaud *et al.* claimed that change of swidden agriculture in Nakai-Nam Theun National Protected Area (NNT NPA) of central Laos has a close connection with biodiversity conservation (e.g., suppressing local wildlife trade) and villagers' livelihoods [144]. Based on the abovementioned case studies, it could be found that the driving forces of swidden system change are variable from place to place. As swidden practice gets more attention, more research should focus on its underlying factors.

5.5. Quantifying the Impacts of Swidden Agriculture Changes

There is no doubt that swidden agricultural systems will face substantial transformations in the future from increasing human activities (e.g., road construction) in SEA [9]. Ethnic minority groups have long been the principal practitioners of swidden agriculture [12]. They usually settle down in remotely upland areas and are tagged as the poverty-stricken. Poverty reduction and improving local livelihoods have always been the top goal for governments. In addition, SEA is one of the three major tropical forest regions [145] and is endowed with extremely rich biodiversity [146]. The pressing problems to be answered are how, in what ways, and to what extent will these unprecedented transitions pose impacts on swidden farmers' livelihoods [65] and cultural identity [66], biological diversity and ecosystem services [64,140].

Transformation of swidden into other land use types usually exerts profound diverse effects on local livelihoods [61]. Traffic infrastructure construction easily promotes the transition of swidden as it allows farmers more opportunities to involve market activities. The involvements in market may attract swiddeners to settle down in lowlands where their livelihood may be challenged and they may lose cultural identity as well [65]. These impacts are fatal for farmers whom are experiencing rapid transformation of swidden. This may be true for swiddeners that live close to a national road but not for others settled in remote, inaccessible locations [84]. Chi *et al.* pointed out that swidden farmers experienced different impacts on their livelihoods under the transition of swidden farming due to the impacts of traffic infrastructure and markets in Northwest Vietnam [84]. Other incentives like governmental agro-forestry policies also lead to the transition of swidden as they are always mandatory. In Northern Laos, swidden agricultural transformation increased the vulnerability of local livelihoods due to national forest conservation and intensive and commercial farming [147]. In the future, more analysis should be done to evaluate the impacts of this land use change due to the increasing economic globalization and regional integration in ASEAN.

A pan-tropical meta-analysis of swidden farming shows that the change of swidden landscape into intensive land use types will increase household incomes in the foreseeable future but lead to negative environmental consequences in the long run [9]. Swidden system is viewed as an effective way for maintaining high levels of biodiversity [64]. However, other studies show that swidden transition does not invariably lead to biodiversity loss but may maintain or strengthen it [140]. Actually, short-term economic benefits are obviously detectable while the possible environmental effects are neither easily quantified nor fully understood so far. Nevertheless, one thing that can be confirmed is intensification or monoculture predicts less biological diversity. A prominent case in montane SEA is the rapid expansion of plantations agriculture, such as rubber, eucalyptus, oak and oil palm. Plenty of related studies normally investigate its impacts on biodiversity and ecosystem services from one or several aspects [148,149]. The transition of swidden usually incurs a series of environmental effects (soil erosion, invasive species, water quality, *etc.*) and overall analysis is scarcely reported.

6. Conclusions

The purpose of this review paper was to give a comprehensive overview of swidden agriculture studies in SEA undertaken in the past two decades. Over 100 peer-reviewed studies (some were special issues papers) published during the last two decades were used to analyze the progress of swidden farming research in SEA; the number of studies and several special issues imply the growing scientific interest in this topic.

Several meaningful conclusions were obtained in this synthesis paper. First, swidden agriculture is more suitable to represent the traditional farming system in SEA because it has a close connection with cultural identity and fire relatedness. Second, swidden agriculture will continue to persist in many remote upland areas of SEA in this century although it is in transition. Since the 1990s, increasing regional economic cooperation between/among nations has greatly promoted rapid urbanization and population growth in SEA [150]. Consequently, human activities have altered the land use and land cover types accordingly, such as tropical forest cover rate decline [151]. Swidden farming used to be a predominant land use type in SEA, yet it has undergone rapid and diverse transition into commercial-oriented land usages due to the seeking of economic opportunities [84,142].

Third, both the scientific community and governmental decision-making departments still face a dilemma of limited data. On the one hand, there are pressing demands for updated and accurate information on swidden agriculture. It serves as the basic data for poverty alleviation of local swidden farmers, and environmental effects' evaluation of swidden farming changes. Yet, much remains uncertain about the population of swidden farmers, and the locations, extent and change of swidden practice [11,12]. On the other hand, swidden agriculture does not gain equal attention as other dominant land use systems, even when viewed in a completely negative light. Therefore, there have been very few thematic maps of swidden agriculture. Our review paper showed that there is an urgent need for monitoring the spatial pattern and temporal change of swidden agriculture.

Fourth, the free availability of satellite imagery provides a solid data basis for carrying out this massive undertaking. Among them, the most noteworthy might be the multi-decadal Landsat historical dataset [152]. To begin with, the Landsat family satellites provide the longest continuous record of the Earth's surface over 40 years. It makes the historical evaluation of dynamic changes of swidden agriculture possible. Then, the medium spatial resolution of Landsat imagery makes it the appropriate classification unit for swidden (or burned plots) identification and mapping. Furthermore, all Landsat family sensors (after Landsat 5) have two SWIR bands which are very sensitive to moisture and soil change after a fire or burning of natural vegetation. One single image acquired after burning or two images before and post-burning may distinguish the burned pixels from the unburned ones. Finally, the parallel orbits of two satellites (since 2000) reduced the repeat coverage of the sensor over the same location on Earth from 16 to eight days. The improved temporal resolution enhances the ability of Landsat imagery in detecting seasonal changes of swidden practice, usually from felling/slashing, sun/air drying, burning and post-burning to crops cultivating. So far, Landsat imagery and its related techniques have been used more frequently in the domains of fire occurrence, burned area and burn severity. As they have a common feature, *i.e.*, fire-related, it is perceived that these consistent images and remote sensing based methods can also be applied in the field of swidden agriculture mapping in this review paper. In the past, several factors may explain why there are limited studies of swidden mapping with Landsat data in SEA. Firstly, the importance of swidden agriculture is not fully acknowledged by governments at different levels, and swidden lands are often relegated as unused or abandoned categories. Secondly, swidden systems are usually more diverse, complex and dynamic than other land use forms. Thirdly, the high cost of Landsat data before 2008 may also limited extensive investigation of swidden agriculture. We believe that the knowledge of swidden farming will be improved.

Fifth, four broad remote sensing approaches can be applied for swidden agriculture mapping. They are spectral signatures based approaches, phenological features based approaches, statistical theory based approaches and landscape ecology based approaches. The common feature between burnt area and swidden agriculture, *i.e.*, fire-related, was highlighted. Burning is an important phase in swidden agriculture. Specific approaches such as the spectral vegetation indices, logistic regression model, ANN and SVM can also be introduced to detect swidden agriculture accurately at the micro-level. Unfortunately, such related analysis of swidden mapping is quite limited. In comparison to conventional remote sensing classifiers, the landscape ecology methods view swidden agriculture as integral rather than a certain phase. These methods delineate swidden cultivation landscapes at the meso-level.

Finally, with the spatial pattern and temporal dynamics of swidden agriculture in SEA, it will serve as basic geographical data for other related studies. First of all, based on the information of accurate locations and spatial extent, it not only contributes to estimating how many ethnic minority farmers undertake or rely on swidden agricultural systems, but also to understanding the temporal dynamics of swidden populations in each country. This knowledge will help to guide improvement of local livelihoods and poverty reduction. Next, in combination with socio-economic, cultural and political factors, it will facilitate quantifying the underlying drivers of why and how swidden changes. In the end, with the distribution map of swidden, it will promote extensive investigation into the potential effects on biological diversity and carbon emission in the transition of swidden agriculture.

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Author Contributions

Peng Li and Zhiming Feng were responsible for the study conception and design. Peng Li, Zhiming Feng and Luguang Jiang contributed to field survey work. Peng Li, Chenhua Liao and Jinghua Zhang performed the literature collection and analysis. Peng Li prepared the drafting of the manuscript. Zhiming Feng and Peng Li obtained funding. All authors made critical revisions to the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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