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Role of an Eco-tour Guide Certification System in Sustainable Ecotourism on Amami-Oshima Island, Japan

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ABSTRACT

Although the goal of ecotourism is to balance tourism with environmental conservation, there are concerns regarding the excessive promotion of tourism. One measure to prevent excessive use is to certify tourism operators. However, certification is inconsistent with regional autonomy, and because it is a voluntary initiative, there may be limitations in its scope. Accordingly, we conducted a case study of a certified eco-tour guide system for Amami-Oshima Island in Japan to determine whether a certification system for eco-tour guides would promote the appropriate use of the environment. This study included interviews with stakeholders and a questionnaire survey administered to certified guides. To obtain certification, guides must complete a training course and possess guide experience. In addition to securing work, the guides also obtained certifications to improve their quality. Guides work at a higher frequency than in other areas. However, concerns arose because of the lack of penalties for self-regulation agreed upon by the Council and the presence of unqualified guides. We conclude that penalties and legal systems should be introduced for malicious cases. In addition, discussions of use regulations should involve both guides and residents in the negotiation process, and a third-party organization should be engaged to provide accreditation, ensuring that the impact of regulations is properly assessed.

Keywords: ecotourism, eco-tour guides, Amami-Oshima Island, certified guides, World Natural Heritage

INTRODUCTION

Ecotourism has attracted considerable attention as a sustainable form of tourism (Harada, 2005; Madhumita and Bani, 2015). An advantage of ecotourism is that a high proportion of the related economic benefits remain in the region and the use of protected areas can be regulated according to residents' opinions (Ito, 1997). Based on these expectations, some researchers have considered ecotourism a tool for regional development (Shikida and Morishige, 2003).

However, there are concerns about ecotourism. One is that ecotourism could lead to mass tourism development that borrows its name (Self et al., 2010; Tanaka et al., 2011). To avoid substantial large-scale development, it is necessary to evaluate the balance of environmental conservation, regional development, and tourism promotion (Madhumita and Bani, 2015; Kaizu, 2016).

Mechanisms are in place to certify regions and guides that meet specific criteria for preventing ecotourism from destroying the environment. One benefit of the tourism certification system is that it presents business challenges that can be addressed, thereby increasing business sustainability (Graci and Dodds, 2015). Specifically, energy use and facility management costs have decreased with certification, because the requirements for certification include items related to environmental considerations (Dziuba, 2016). Government support for management has also been encouraged (Botero and Zielinski, 2020). Moreover, certification increases the likelihood of attracting environmentally-conscious travelers (Jorge, 2002; Fogle and Duffy, 2018). The accreditation body charges a fee for certification, although the amount varies depending on the size of the business (Holub, 2015). The expenses and efforts to obtain certification can be burdensome (Margaryan and Stensland, 2017; Gkoumas, 2019). Small businesses with limited funds and labor may find this burden even more severe.

Research on eco-labels can be helpful in terms of showing environmental considerations. Eco-labels, which are symbols or seals, assist consumers in identifying products and services that are environmentally superior, thereby boosting their confidence in making eco-friendly purchases (Darnall et al., 2018). Studies on eco-labeling in relation to tourism have shown that four

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Table 1. Summary of the guides among the interviewed subjects

	A	B	C
Gender	Female	Male	Female
Hometown	Amami Island	Amami Island	Outside of Kagoshima Pref.
Guide work history	3 years	17 years	26 years
Tour Contents	Wildlife observation on Santaro City Road Canoeing in mangrove forests	Guide to Kinsakubaru Native Forest Canoeing in mangrove forests	Assistance of diving and other marine activities Guide to Kinsakubaru Native Forest
Types of employment	Multiple jobs (Self-employed)	Full-time (belonging to a company)	Full-time (Self-employed)

[1] To avoid any disadvantage to the research subjects in conducting the research, we followed the "Research Guidelines Based on the JSS Code of Ethics" established by the Japan Sociological Society. In accordance with these research guidelines, we informed the research subjects of the purpose of the research and obtained their consent. Furthermore, we anonymized the names of the research subjects with regard to matters that may cause them to suffer disadvantages.
[2] Class 2 driver's license: Required when operating a commercial passenger-carrying vehicle such as a taxi, stipulated in Articles 84 and 86 of the Road Traffic Act.

conditions are necessary: (1) broad coverage and penetration, (2) well-defined and transparent entry criteria, (3) independent audits, and (4) penalties for non-compliance (Buckley, 2002). On the other hand, Buckley's (2002) discussion focuses on the acceptance of ecolabels in the marketplace, and it is debatable how these four conditions are actually considered. Several discussions (Honey and Rome, 2001; Graci and Dodds, 2015; Bučar et al., 2021) define certification in tourism as "voluntary initiatives." These voluntary initiatives are expected to be limited in their efforts related to examinations and penalties because of concerns regarding the lack of funding and staffing of the institutions that perform certification (Haris and Jago, 2001). In addition, from the perspective of community autonomy, there is a concern about the contradiction between the certification process, which presents the desirability of tourism, and local autonomy (Klintman, 2012; Kenchu, 2021). The unconditional affirmation of third-party audits may deprive regions of autonomy. However, the absence of audits and penalties may lead to invalidation of the certification system. Therefore, the validity of ecotourism certification remains a subject of debate.

In addition, the benefits of ecotourism may be concentrated in specific individuals or groups (Kandel et al., 2020) or in entities outside the region (Harada, 2005). Thus, paying attention to whether revenue from ecotourism spreads to small businesses is important when considering the development of an entire region through ecotourism.

Therefore, this study views guides as small-scale tourism businesses and examines the impact of the certification system on them. As previously mentioned, a guide certification system has been implemented on Amami-Oshima Island. Using Amami-Oshima Island as a case study, we provide recommendations on whether a certification system for eco-tour guides can fulfill the criteria of appropriateness of environmental use.

RESEARCH METHODOLOGY

Research Method

The research methods included a literature review, stakeholder interviews, and questionnaire surveys with certified eco-tour guides (hereinafter referred to as "certified guides").

Stakeholder Interviews

Interviews were conducted with eco-tour guides, organizations related to ecotourism, and local governments. The interviews included questions related to the background that led to the introduction of ecotourism, and the current status and challenges of the institutional ecotourism framework.[1] The interviews were conducted over 20 days from November to December 2021, May 2022, November 2022, and March 2023.

Table 1 shows the summary of interviewed participants. Guides A and B worked outside the island after graduating from high school and then returned to Amami-Oshima Island to start their guide businesses. Guide C was an immigrant from outside Kagoshima Prefecture who had worked for a company engaged in marine activities and had started her own guide business. In the interviews conducted prior to this study, many of the guides reported being born in the Amami Islands. Therefore, three groups of guides were selected: guides who are local and have been in the guiding business for a short time, guides who are local and have been in the guiding business for a long time, and guides from outside Amami-Oshima Island. In addition, we obtained testimony that only a few companies were engaged in the guide business as a company, and that most companies were sole proprietors. Therefore, the survey targets were selected by considering different forms of guide employment.

Questionnaire Survey

The questionnaire asked certified guides about their guiding practices, motives for obtaining certification, and problems with or motivations for the certified guide system. Regarding the number of guided tours, we asked about the number of jobs per year in 2019 and in 2021.

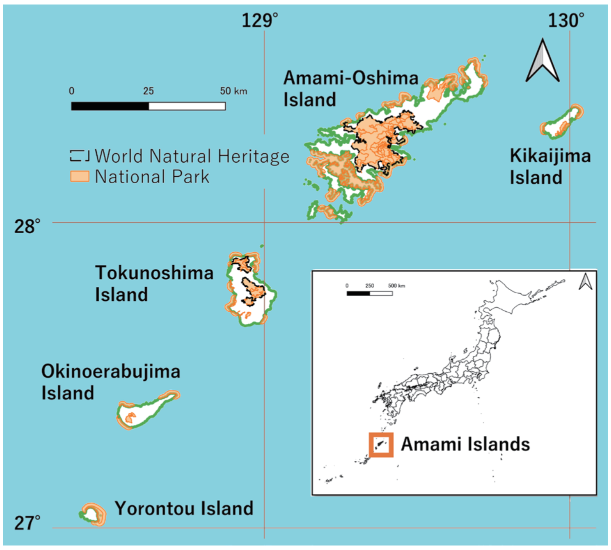

Fig. 1. Map of Amami Islands.

Source: Prepared by the author using data from the National Land Information Division, Ministry of Land, Infrastructure, Transportation and Tourism, Japan, and the Biodiversity Center, Ministry of Environment, Japan

Note: Islands names are listed only for islands where a Liaison Council exists.

The questionnaire was developed by adding and changing questions based on a questionnaire survey targeting the "National Government Licensed Guide Interpreter" (Ministry of Land, Infrastructure, Transport, and Tourism[MLIT], 2008; Okinawa General Affairs Bureau, Cabinet Office, 2015). The National Government Licensed Guide Interpreter is a national qualification in the guide business. The 2008 MLIT survey was administered to National Government Licensed Guide Interpreters nationwide. The 2015 survey was conducted using National Government Licensed Guide Interpreters in Okinawa Prefecture, Japan. This survey aimed to pinpoint particular needs for tourism in Okinawa and issues concerning the reception of tourists. Okinawa is located south of the Amami Islands and was registered as a World Heritage Site at the same time as Amami-Oshima and Tokunoshima Islands. However, because Okinawa has been more active in tourism efforts than Amami (Government of Japan, 2019), questionnaire in this research was developed based on a survey conducted in Okinawa. Of the 137 guides registered as certified guides, 134 were included in the survey, excluding 3 who declined the survey because they were not engaged in the guide business. The questionnaire survey was conducted between August and October 2022.

The questionnaire was distributed to the Wide Area Administration Association of the Amami Islands, which oversees the certified guide program. Responses were collected by mail to Nagoya University and via Google Forms, a web-based service; 36 valid responses were received by mail and 13 by Google Forms for a total of 49 responses (36.6% of those surveyed).

Research Site Overview

Fig. 1 shows a map of the study area. The Amami Islands in southern Japan have a humid subtropical climate. Administratively, Amami Islands are classified as belonging to Amami City and Oshima County, Kagoshima Prefecture. Of these, Amami City on Amami-Oshima Island has the larger population (Kagoshima Prefecture, 2024). The remoteness of the Amami Islands from the mainland and the declining population due to a low birthrate and an aging population have resulted in poor economic development (Ikeda, 2021). The Amami Islands were registered as a national park in 2017 and as a World Natural Heritage Site in 2021 because of their endemic ecosystems (Amami City, 2021). The number of visitors is expected to increase because the region is registered as a national park and a World Heritage Site (Amami Islands Ecotourism Promotion Council, 2017), and balancing environmental conservation and economic development is needed (Onodera, 2022).

Koike (2022) noted that only after the 1970s did tourists visit the Amami Islands because of an increase in diving and other recreational activities. In the late 1990s, tourism in mangrove forests and other forested areas began to take place (Song, 2020), and tourism activities became more diversified (Kiyose et al., 2021) In 2001, Kagoshima Prefecture promoted World Natural Heritage registration as a key policy, and environmentally friendly tourism (ecotourism) began to be considered for introduction (Song, 2017).

Regarding local ecotourism, some studies have focused on the relationship between the rules of use and guide users (Mitsui and Kubo, 2018), reported the current status of ecotourism (Kaizu, 2022), examined the ecological impacts before and after registration as a World Heritage Site (Suzuki et al., 2022), and discussed the impact of World Heritage registration from the perspective of tourism promotion (Koike, 2022). However, no studies have investigated the current status and challenges of guiding businesses in Amami or the impact of obtaining certification.

RESULTS

Overview of System and Framework Related to Eco-tour Guides in Amami-Oshima

Eco-tour guides include assisting marine activities, observing wild flora and fauna, canoeing through mangrove forests, and exterminating invasive alien species (Amami-Oshima Island Ecotourism Liaison Council, 2022). There are some categories (e.g., forest, ocean, and village areas) in which each guide operator provides guided tours.

Eco-tour guides are registered with the "Ecotour Guide Liaison Council" (hereinafter referred to as the Liaison Council) on each island. On Amami-Oshima Island, registration with the Liaison Council and working as a guide necessitates completion of the initial stage of training for eco-tour guides. This training program started in 2014 and consists of 20 lectures over two years to cultivate basic knowledge of guides. The content is supervised by academic experts and covers topics ranging from knowledge

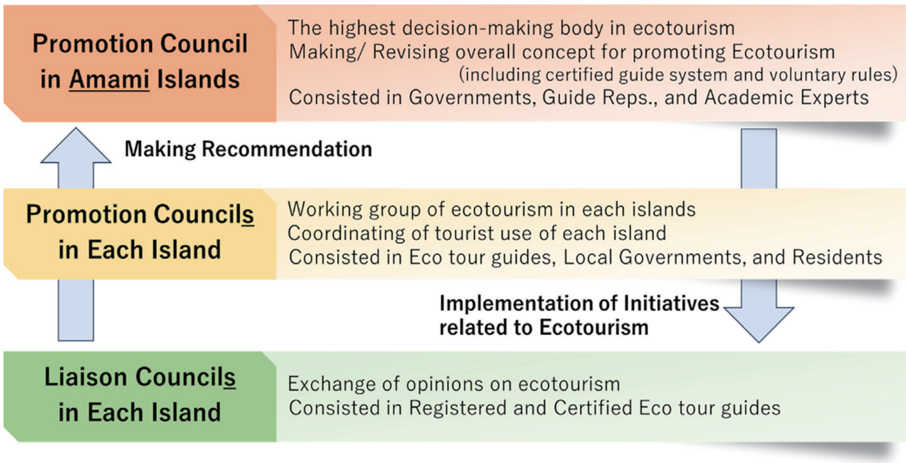

Fig. 2. Organizational structure related to ecotourism.
Source: Prepared by the author by Amami Islands Ecotourism Promotion Council (2017)

of the local environment to emergency response and hospitality. In the second year of training, the participants are divided into guide and tour participant roles and provided a tour demonstration. As one could not complete the course after missing even one lecture, the total number of participants was 750, and the total number of graduates was 262. Upon completion of the initial training, the guides may act as registered guides.

After completing the initial training stage, the guides can apply to become certified guides if they meet certain requirements, such as a history of local residency or passing a paper-based test. Certified guides are defined as those with an in-depth knowledge of the nature and culture of the Amami Islands. Also, certified guides are responsible for conserving the local environment and providing visitors with safe and high-quality experiences. The certification allows the guides to guide visitors to areas where entry is restricted from the viewpoint of environmental protection (Kinsakubaru Native Forest and Santaro Line area, hereafter referred to as "restricted areas") and to transport participants without a class 2 driver's license.[2]

The certified guide system was initiated in 2016 and 137 people had been certified as guides as of the survey date. In 2020, certification requirements were updated, and performance requirements, such as the number of times a guide has guided for a fee, were added to the list of requirements. Certified and registered guides receive a sticker to display on the vehicle carrying guide users so that they can be identified as certified or registered guides. In summary, there are two levels of training related to guiding. Registered guides who have completed the initial training stage can obtain certification for paid guiding experience.

The Promotion Council on each island makes recommendations for the guide registration and certification system and the voluntary rules described below. The Amami Islands Ecotourism Promotion Council holds the highest decision-making authority (Amami Islands Ecotourism Promotion Council, 2017). Fig. 2 illustrates the ecotourism-related organization. The certified and registered guides belong to the Liaison Councils shown at the bottom of the figure. The Promotion Councils on each island in the center of Fig. 2 comprise local government officials, eco-tour guides, representatives of community organizations and fishery associations, and forestry association officials. The upper part of Fig. 2 depicts the Amami Islands Ecotourism Promotion Council, which makes final decisions on ecotourism-related initiatives with the participation of officials from the Ministry of the Environment and the Forestry Agency, as well as academic experts.

The chairperson of the Liaison Council in Amami-Oshima Island responded, "Representatives of residents and users of the sea and mountains are included in the Liaison Council. Selection of participants is based on the idea that nature has been preserved because of the people who have used it." He recounted regarding the first meeting, "At first, the direction of the meeting was not clear. Each participant was saying what he or she wanted to say." However, at the most recent meeting, he said that discussions on the future of ecotourism had been held and that the understanding of ecotourism among meeting participants had deepened. He was surprised to hear someone he had never expected to speak about the future of ecotourism, indicating that he sensed a more profound understanding among the participants. Regarding consensus-building among the participants, an Amami City official stated, "I think it was easier to obtain participants' understanding of the regulations and use of the area. The reason for this may be that the guides, not a government official, serve as the chairpersons of the Council."

The Liaison Council also formulated voluntary rules for guiding activities, including the driving speeds of cars for wildlife observation, the number of vehicles allowed to enter a restricted area, and what to do if an exotic species is discovered. Voluntary rules require reservations for entry into restricted areas. Additionally, visitors should be accompanied by a certified guide when entering restricted areas. In September 2022, an experimental use quota was established to allow residents who were not guides to enter restricted areas. Amami City officials explained that this was intended to allow residents to use the restricted area, assuming that residents guided their acquaintances. The city planned to discuss the possibility of increasing or decreasing the number of slots used by residents based on the results of the demonstration experiment.

As described above, the guide took the initiative in building a consensus on using the environment with the participation of residents who regularly used the environment. Additionally, the rules of use were frequently adjusted to incorporate resident requests. However, some stakeholders have raised concerns. The Chairperson of the Liaison Council considered some residents and guides not following voluntary rules as constituting an issue. Some guides who had not been certified guided visitors through restricted areas (Nankai Nichinichi Shimbun, 2019). When we entered the restricted area with a certified guide, we confirmed the presence of tour guides guiding participants who exceeded the maximum allowed number set by the voluntary rules. The Liaison Council also discussed penalties and legal backing (Nankai Nichinichi Shimbun, 2019). The chairperson of the Liaison Council explained that although measures such as suspending operations for a certain period could be considered, "we are currently limiting ourselves to verbal warnings because their livelihood depends on the guide business." Guide C stated, "Even within the Liaison Council, opinions on the regulation of ecotourism differ. Individual guides must be autonomous to reduce their burden on the environment." As of the survey date, there were no penalties for deviation from voluntary rules, and the use of the area depended on the guides' voluntary efforts.

In relation to deviations from voluntary rules, we also asked about legal support in restricted areas. However, an Amami City official explained that regulating the number of vehicles passing through a restricted area is difficult because some areas are city roads. Regulating traffic for purposes other than "preserving the structure of the road or preventing traffic hazards" is difficult (Article 46, Road Act). An Amami City official also stated that some residents use the road for purposes other than observing wild animals and plants. In addition, the city office has received comments from residents who did not feel comfortable with the regulations.

In summary, two levels of training were provided to the guides, which ensured their understanding of the environment and quality assurance. Furthermore, a consensus-building forum was established with the participation of residents who normally use the environment, and adjustments were made to usage rules, such as the establishment of usage quotas by residents. However, only unenforceable penalties are imposed for deviations from voluntary rules, and there is currently no legal backing for such penalties.

Current Status of the Eco-tour Guide Business

In this section, we examine the status of the certified guide system and eco-tour guidance based on the results of a questionnaire survey. Fig. 3 shows the age structure of the respondents, with the largest number in their 60s, followed by those in their 50s and 40s. In the Okinawa Survey (Okinawa General Affairs Bureau, Cabinet Office, 2015), which was used as a reference

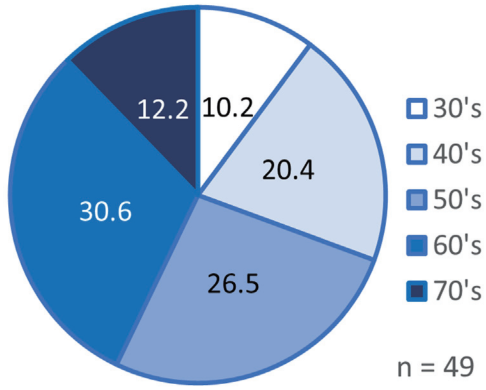

Fig. 3. Age structure of the respondents (n= 49).
Source: Prepared by the author from the questionnaire survey, same as below.

when preparing the questionnaire, the largest number of respondents were in their 40s, followed by those in their 60s or older, and then those in their 30s. Compared to Okinawa, the ratio of guides in their 50s and 60s was higher. Guide C stated that the reason for the large number of older guides is that the income from the guiding business is not stable; therefore, the proportion of older people who can work in it during their leisure time with their pension income may be high.

The gender of the respondents was 38 (77.6%) male, 9 (18.4%) female, and 2 (4.0%) non-responsive. Given that 33.0% of the respondents in Okinawa were male and 67.0% female, the percentage of male workers was high.

Regarding the type of employment, 16 respondents (32.6%) were full-time guides, 29 (59.2%) had a main or side job in addition to guiding, and 4 (8.2%) had obtained certification but did not work as guides. This survey revealed that more than 90% of respondents were employed as guides. Compared to 30% (MLIT, 2008) and 50% (Okinawa General Affairs Bureau, Cabinet Office, 2015) of the respondents to other surveys working as guides, this indicates a high percentage of certified guides engaged in the guide business.

Regarding side businesses, while some were related to tourism, such as lodging or souvenir stores, others were not, such as farming or working as local welfare commissioners. Among the guides interviewed, Guide A was engaged in guiding, crafting experiences, and arranging films for TV programs. Guide C also explained that although she is currently a full-time guide, she had worked as a district head. Guide A cited two reasons for starting a side business: gaining knowledge about Amami, and dealing with a situation in which she could not guide due to bad weather. Guide C also stated that he began guiding in the Kinsakubaru Native Forest as a substitute activity when the sea was rough.

Fig. 4 illustrates the annual number of guided tours conducted between 2019 and 2021. The number was calculated after excluding responses such as several times and year-round. Responses regarding the number of working days, such as 20

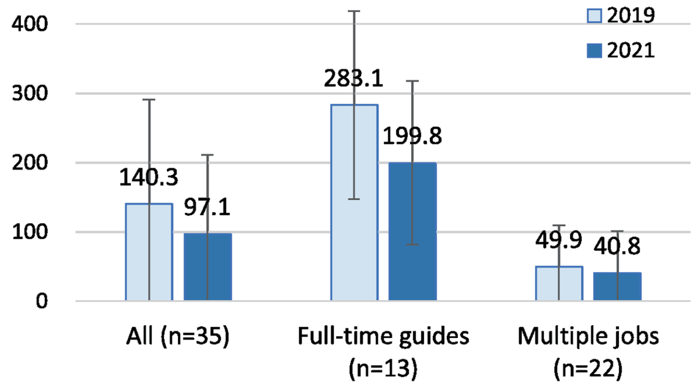

Fig. 4. Number of annually conducted tours in 2019 and 2021.

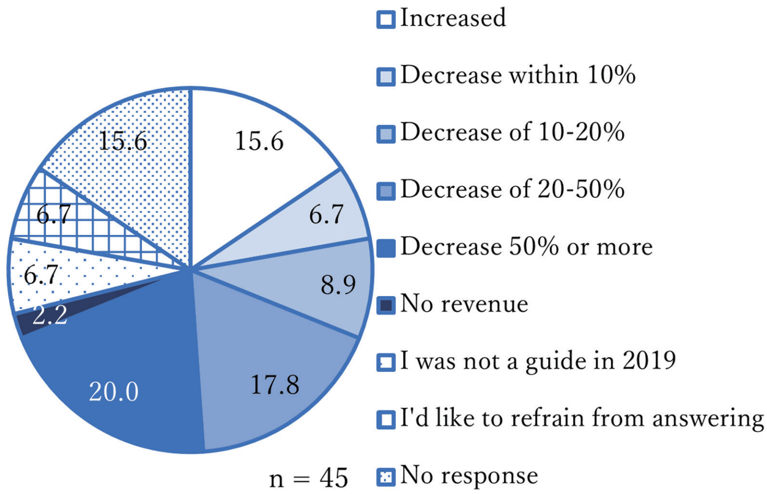

Fig. 5. Change in guide income due to COVID-19 (n= 45).

days, were converted to the number of tours by taking the tour frequency as once a day based on the suggestion (Ministry of Environment, 2008) that most eco-tour itineraries on the Amami Islands consist of one- or half-day tours. As a result, a total of 35 valid responses were obtained. The average number of tours in 2019 was 140.3 (±150.5), with a maximum of 600 tours and a minimum of 2. The average number of tours in 2021 was 97.1 (±114.5), with a maximum of 500 and a minimum of 2. No significant differences were observed between 2019 and 2021 (p = 0.267). Among full-time guides, the number of tours was 283.1 (±136.0) in 2019 and 199.8 (±117.7) in 2021, while among the guides with multiple jobs, the number of tours was 49.9 (±59.6) in 2019 and 40.8 (±60.4) in 2021. In the MLIT survey, more than half of the respondents answered that they guided by themselves 1–30 times per year, suggesting that even those with multiple jobs engaged in the guiding business relatively frequently. This may be because a certain amount of paid guide experience is required to obtain certification.

Fig. 5 shows the changes in guide income associated with COVID-19. More than half of the respondents indicated that their income had decreased, and 20% of the respondents indicated that their income had been reduced by 50% or more, which, combined with the decrease in the number of jobs mentioned above, negatively impacted their income. In addition, we were able to identify only one response stating that the guide was suspended because of the COVID-19 pandemic. Despite the negative impact on income, most respondents continued to operate their businesses.

Fig. 6 illustrates the problems associated with working as a guide. In this question, respondents were prompted to provide up to three answers, except for the option 'none in particular'. Although no responses were received regarding lack of time, the difficulty balancing main and side jobs, or difficulty securing guide work among those working full-time, such responses were found among those working multiple jobs and those not working as guides. This suggests that multiple job groups considered securing guide services a problem. The implementation of side jobs and diversification of guide locations can be viewed as a response to securing guide services.

Thus far, we have examined the eco-tour guide business in terms of the number of jobs and the stability of guide businesses. A high percentage of certified guides work and both part-time and full-time guides frequently conduct guided tours. In addition, the interviewed guides were found to implement side jobs

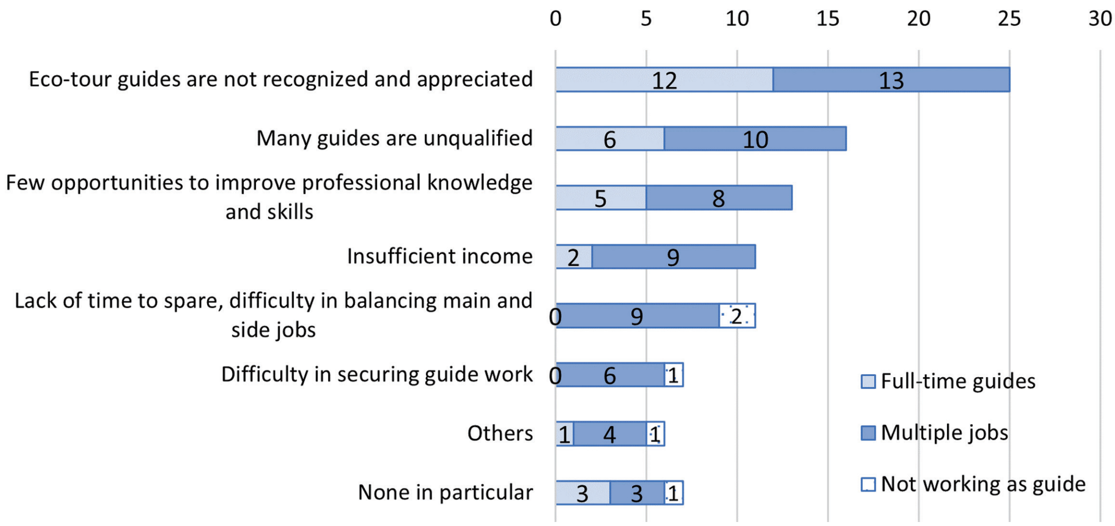

Fig. 6. Problems in working as a guide (n= 49).

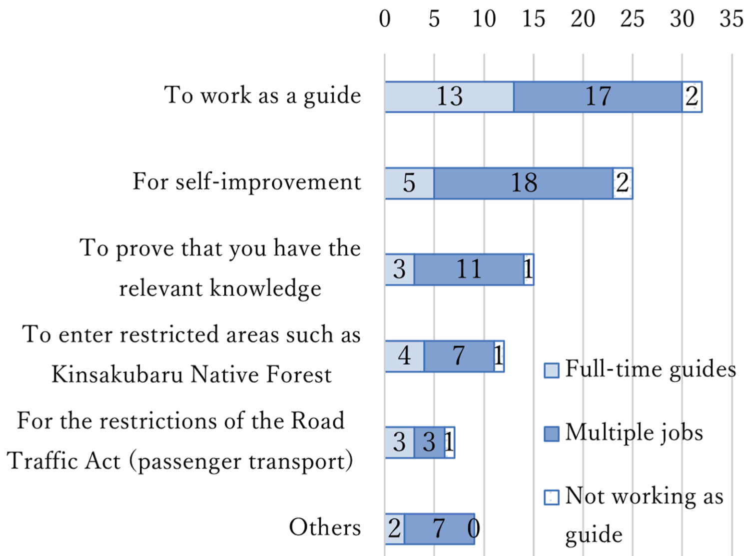

Fig. 7. Motivation for obtaining certification (n= 49).

or diversify their guiding locations to stabilize their income.

Survey on the Intentions toward Certification System

This section examines the intentions toward a certified guide system. Fig. 7 shows the motivation for obtaining certification. In this question, respondents were prompted to provide all applicable answers. In all, 32 respondents (65.3%) obtained certification as guides. In Okinawa, which was used as a reference, 46.4% of the respondents answered, "obtained qualification to work as guides." Although there was no significant difference between the two groups (p = 0.052), there was a slightly stronger tendency to obtain certification in Amami with employment. Many respondents, especially those working concurrently as guides, cited "self-improvement" as their motivation, whereas in Okinawa, 37.5% of the respondents answered "for self-improvement." The difference between this survey and that in Okinawa was statistically significant (p = 0.039), suggesting that the respondents intended to improve their guiding skills through certification.

Fig. 8 shows the skills that respondents wanted to improve as guides. In this question, respondents were prompted to provide up to three answers, except for the option 'none in particular'. The number of responses of "Knowledge of the environment in Amami" and "Knowledge of the history and culture of Amami" were higher than those of "On-the-job training on tourist guidance" and "Knowledge of tourist trends." This suggests that respondents intended to further develop their expertise in the local environment, history, and culture.

Fig. 6 illustrates the problems associated with working as a guide. One item that attracted many responses was "Eco-tour guides are not recognized and appreciated." In Okinawa, "Difficulty in securing work" and "Insufficient income" were fol-

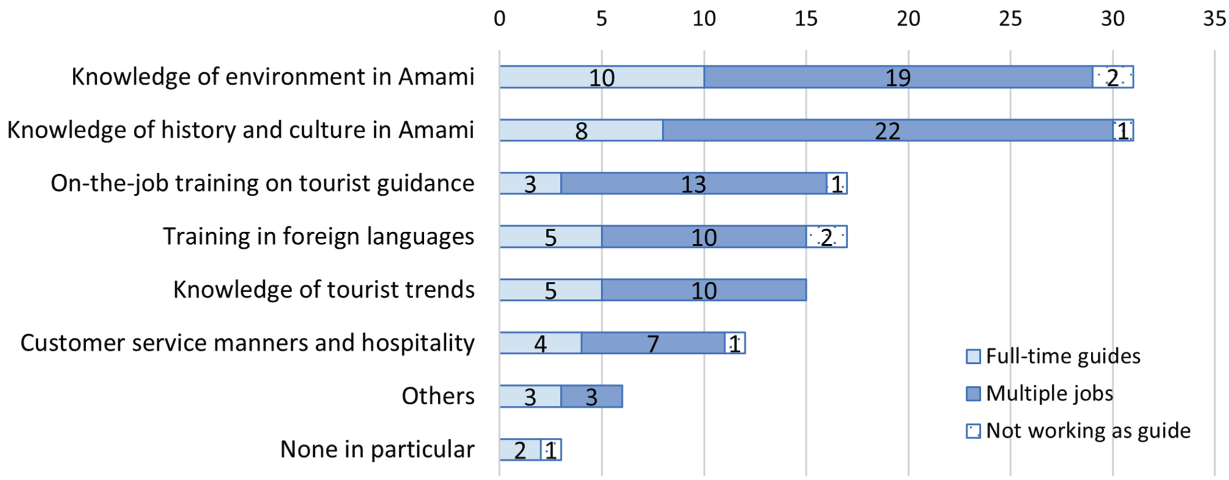

Fig. 8. Skills that respondents want to improve as a guide (n= 49).

lowed by "Interpreter guides are not recognized and valued." In Okinawa, low income or few jobs was perceived as more of an issue than the lack of guide system recognition. Thus, the survey indicated that respondents considered the recognition of eco-tour guides a major issue.

Approximately 30% of the respondents cited many guides being unqualified as an issue. The Wide Area Administration Association of the Amami Islands, which is in charge of the certified guide system, commented, "We can warn guides who are not certified and falsely claim to be certified. However, the Liaison Councils on each island manage guides who have completed the initial stage of training but have not yet obtained certification (registered guides). If the Wide Area Administration Association gives guidance on registered guides, this may cause tension in the relationship between the Wide Area Administration Association and Liaison Councils.

The Wide Area Administration Association also explained that it has becomes difficult to provide legal support for the transportation of passengers by guides who do not have certification. In Amami, certified guides or drivers with Class 2 driver's licenses can drive with tour participants. However, some operators who do not fall into these categories may transport tour participants. If they claim that they are transporting their relatives rather than guide users, it is impossible to sue them. From this point, differences in organizations with jurisdiction sometimes make it difficult to pay attention, and policing on passenger transport has proven difficult.

Thus far, we have examined the intentions toward the certification system. As a motive for acquiring certification, in addition to employment as a guide, respondents wanted to enhance their expertise in the local environment, history, and culture. However, there was a lack of recognition of the certified guide system. Illegal activities by unqualified guides were found to be difficult to control.

DISCUSSION AND CONCLUSION

In this section, we discuss the conditions under which a certification system can promote sustainable tourism based on Buckley's four conditions described in the Introduction. Of the four conditions, we focus on independent audits because of conflicts with local autonomy and the certification process. We also focus on penalties for non-compliance; the voluntary nature of certification makes its effectiveness uncertain.

Independent Audit

On Amami-Oshima Island, the guide takes the lead in determining how regulations should be implemented. The Promotion Council is composed of members of the Ministry of the Environment, the Forestry Agency, and academic experts. These academic experts oversee the initial training course for prospective registered guides. Instead of a direct involvement in local ecotourism, its role can be viewed as monitoring its implementation. Moreover, Amami City officials testified that the guides take the lead in determining how regulations should be enforced, facilitating residents' understanding. A previous study reported that residents' participation in tourism-related activities helped preserve the local environment and culture (Walter, 2009). From a regional development perspective, regional actors should take the lead in regulations and resource management (Nakagawa et al., 2013).

However, as explained in the Introduction, there is also a concern about excessive promotion under the guise of ecotourism. In some cases of resident-based tourism, the lack of governance by administrative entities has disregarded the principle of respecting the autonomy of local communities (Iwai, 2017). By disregarding the purpose and philosophy of certification, not only has the relationship between the environment and local communities worsened (Wieckardt et al., 2022) but also leads to so-called "greenwashing" that misleads tourists about environmental concerns (Self et al., 2010; Heras-Saizarbitoria et al., 2020). In addition, the certification process denies local autonomy. Therefore, it is necessary to survey the entities that administer certification to determine whether they respect regional autonomy.

Therefore, the region must be involved in determining how regulations should be enforced, and a third party outside the region must provide accreditation to ensure that the use and regulation of the system are not excessively promoted. In the Amami Islands, the national government or Promotion Council of the Amami Islands may play the role of auditing certification bodies and implementing accreditation. However, as the relationship between the Promotion Council and each island's Liaison Council has not been fully investigated, this is an issue for future research.

Penalties for Non-compliance

In the Amami Islands, two levels of training were conducted to obtain certification: initial stage training to become a registered guide and training to obtain certification. The respondents had obtained certification to work as guides and were seeking to expand their knowledge of Amami. The results of this study do not indicate a causal relationship between certification and increased employment opportunities. However, the fact that many respondents wanted to deepen their knowledge of Amami suggests that sharing local knowledge may increase job opportunities.

The importance of training for tour guides has been highlighted (Christie and Mason, 2010), although there are limited opportunities to improve knowledge and skills as a group due to a failure to update the course content (Morishige, 2018). Morishige proposed that by sharing their interests, guides can enhance their knowledge and skills. Therefore, incorporating the preferences of guides and offering training programs may serve as a motivation for achieving certification. As explained in the Introduction, certification is expected to increase the number of tourists, while posing difficulties for small businesses due to the cost and burden of the application. For small businesses, the connection between knowledge or technological enhancement and certification may serve as an incentive to obtain certification.

However, since deviations in voluntary rules occurred even after the training course had been completed, the training course may not have prevented deviant behavior. There are no enforceable measures against deviations, and many voluntary rules are left to the discretion of the guides.

As for voluntary rules, while self-regulation can be more flexible than regulation based on the legal system, there is a risk that regulation may not function adequately if the checking system is insufficient (Sagara, 2003). In Japan, penalties for acts that adversely affect flora, fauna, and ecosystems are not fully functional (Takahashi, 2022), and there are concerns about the negative impacts on wildlife with the increase in the number of guided tours in Amami-Oshima Island (Suzuki et al., 2022). Therefore, penalties for malicious cases will likely become necessary in the future.

Furthermore, the absence of free-riders using the natural environment without a regulatory framework leads to compliance with self-regulation (Student et al., 2016). Cases of deviation from regulations should also be analyzed to ensure more effective regulation. However, because the questionnaire survey was conducted via the Wide Area Administration Association, which coordinates the guide certification system, it is possible that guides who hold negative views of the Association and its initiatives did not respond. In other words, the questionnaire might have been biased toward positive responses regarding the Association and its initiatives. Therefore, we have not been able to fully discuss the intentions of guides who deviate from voluntary rules, or the background of such deviations. This will be a subject of future research.

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Article

Quality of Threshold Accepting Heuristic Search Results When Attempting to Solve Forest Harvest Scheduling Problems

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ABSTRACT

Threshold accepting is a *s*-metaheuristic, local search process that moves from one solution to another within the feasible region of the solution space via a random change to one or more elements of the solution. Threshold accepting can be further characterized as an aspirational combinatorial optimization process that does not guarantee optimality. The quality of outcomes from a threshold accepting search process varies when applied to forest harvest scheduling problems depending on the parameter value assumptions and sub-processes employed. Two relatively small but realistic case study forests are subjected to four management scenarios and outcomes are examined to illustrate how the quality of solutions may differ when the parameter values and processes employed within threshold accepting are adjusted. Statistically significant improvements in solution quality were generally evident with a slowing of the rate of change in the threshold value and the enhancement of the search process by using 2-opt moves and search reversion. While it was rarely observed, the threshold accepting heuristic search process located the optimal solution of most of the problems modeled. In cases where the problems involved maximizing an economic objective, about 47% of the heuristic search solutions had an objective function value that was within 1% of the optimal solutions.

Keywords: forest management, forest planning, combinatorial optimization, heuristic

INTRODUCTION

Many contemporary forest harvest scheduling problems require the use of discrete decision variables and mixed integer problem formulations. The desire to control the timing, placement, and size of final harvest activities is one example. The development of feasible and efficient solutions for mixed integer programming problems can be arduous with respect to the computing time required. Mathematical programming using exact or algorithmic methods represents the act of locating an optimal solution to a problem which was expressed using mathematical notation (Killen, 2021) using procedures that can guarantee locating the optimal solution (Romanycia and Pelletier, 1985). These methods are the preferred approach for forest harvest scheduling efforts, however, the challenges related to environmental concerns have prompted the need for integer decision variables, and thus some contemporary forest harvest scheduling problems are difficult or impossible to solve with exact methods (Brodie and Sessions, 1991). Due to these challenges, heuristic search processes have been suggested as potential methods to assist with forest harvest scheduling efforts.

S-metaheuristic search processes operate one level above basic move selection search processes (e.g., hill-climbing or random search) in navigating through a solution space (Albus, 1981). These types of search processes capitalize on insight or knowledge gained during recent search activity (Romanycia and Pelletier, 1985). Originally proposed by Dueck and Scheuer (1990), a threshold accepting search process is considered a *s*-metaheuristic (Talbi, 2009), a unidirectional approximation algorithm for solving complex problems (Siedentopf, 1995), and a refined local search algorithm (Winkler and Fang, 1997). One solution to a problem is maintained in computer memory at any one point in time during the search process, and an adjustment (a move within the neighborhood of the solution space) is made to convert this solution to a slightly different solution in the local neighborhood of the solution space. As with simulated annealing, a potential move is randomly selected from the set of possible adjustments to the current solution. In forest harvest scheduling, for example, a move might consist of randomly selecting a stand of trees, then randomly selecting a different year in which these trees will be harvested. The objective function value and the constraints are then assessed, and the move is potentially accepted.

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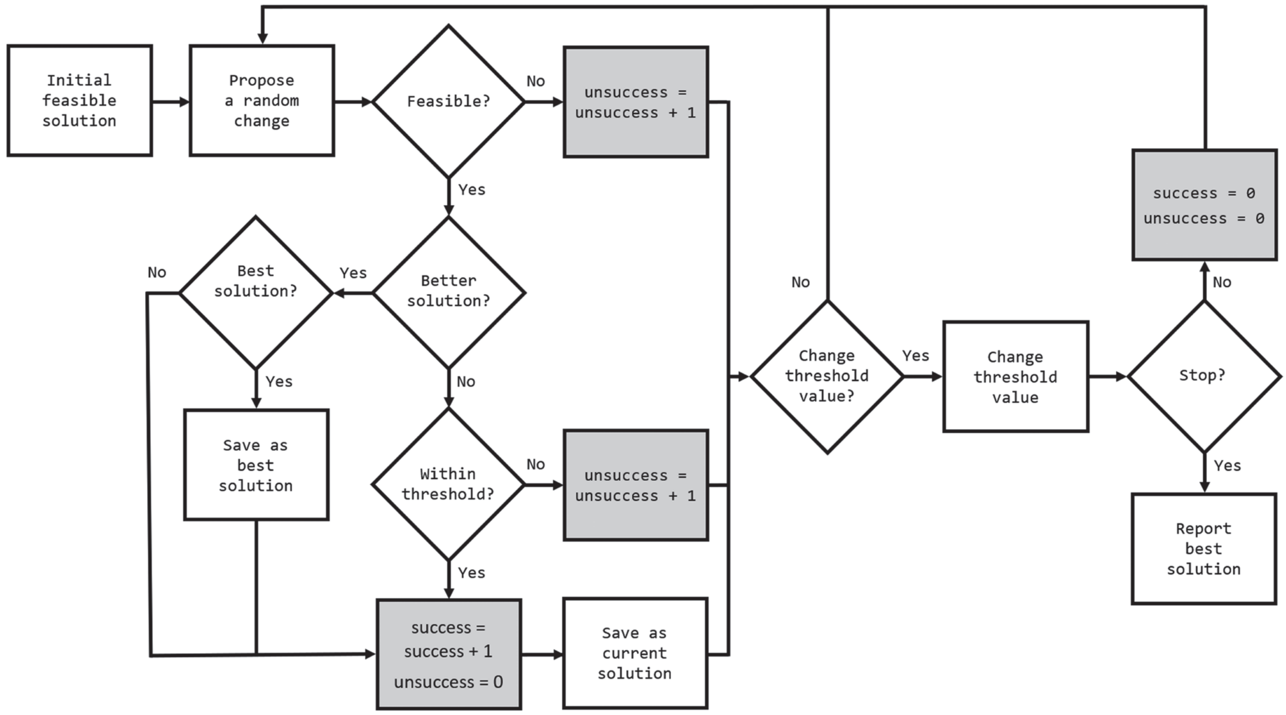

Fig. 1. A general flow chart of the threshold accepting heuristic search process.

Threshold accepting is very similar in concept and structure to simulated annealing, except for the manner in which it decides whether inferior moves suggested by the search process are acceptable. As others have noted (Nissen and Paul, 1995), a threshold accepting search process is a simplification of a simulated annealing search process. Both search processes attempt to change a current feasible solution to a new feasible solution through a random perturbation of the current solution. When the proposed change leads to a higher quality feasible solution (as reflected in an improvement in the objective function value), both search processes automatically accept the proposed change, and the new solution becomes the current solution (Fig. 1). When the proposed change leads to a lower quality feasible solution, the search processes differ in how they decide whether to accept the change (even though it may lead to a lower quality solution) or to reject the change. When using a simulated annealing search process a change to a lower quality solution is acceptable with a given probability that is a function of how long the search has been conducted (as reflected by the current *temperature* of the annealing process) and the difference in objective function values between the proposed feasible solution and the current (or often the best) feasible solution. The temperature value within a simulated annealing search process begins relatively high and decreases as the search progresses. The probability of acceptance then decreases as the temperature value decreases (as the search progresses) and as the difference in objective function values increases.

The simplification employed within threshold accepting involves replacing the probability of acceptance with a straightforward assessment of the difference between the objective function values of the proposed, temporary solution and the current (or best) solution. So, if a proposed feasible solution has an objective function value that is lower in quality than the objective function value of the current (or best) solution that is held in memory, yet the difference between the objective function values of these two solutions (the proposed solution and either the current or best solution) is smaller than the current threshold value, the temporary solution is deemed *acceptable*, and it becomes the current solution. However, if the difference between the objective function values of the two solutions (the proposed solution and either the current or best solution) is larger than the current threshold value, the temporary random adjustment is discarded (the proposed solution is rejected) and the search reverts back to the previous feasible solution to the problem. The threshold value within a threshold accepting search process begins relatively high and decreases as the search progresses. At some point the threshold becomes zero (0) and the search process becomes a local hill-climbing search. Threshold accepting may be conceptually easier to comprehend than simulated annealing because the threshold value is represented with the same units as the objective function value of the problem being solved. For example, if an objective function is designed to assess the value of a harvest schedule in Japanese Yen, the threshold value is also represented as Japanese Yen rather than a probability of acceptance.

From the description provided here it is evident that threshold accepting is a somewhat discriminatory, somewhat forgiving, stochastic hill-climbing search process. In part due to its speed and simplicity, threshold accepting has been used in forestry to address complex forest harvest scheduling problems (Bettinger et al., 2002; Bettinger et al., 2003; Bettinger and Boston, 2008; Zhu and Bettinger, 2008; Li et al., 2010; Bettinger et al., 2015; Akbulut et al., 2017) and has been used to address complex problems in a wide variety of other domains of commerce (e.g., Tarantilis et al., 2004; Perea et al., 2008). Other tangential issues in forest management can be addressed as well with a heuristic approach such as this. For example, with the assistance of a threshold accepting search process, Marshall et al. (2003) illustrated how smaller land units constructed within a geographic information system allow greater flexibility in the scheduling of management activities with a threshold accepting search process. And, Coulter et al. (2006) illustrated how a threshold accepting search process could be used to maximize the value of a schedule of forest road maintenance activities that are subject to budgetary constraints.

The objective of this paper is to illustrate how the outcomes from a threshold accepting search process may change as the parameters of the search change, and as sub-processes are added to facilitate diversification and intensification of the search. Statistical tests are employed to assess whether two sets of solutions developed utilizing different search assumptions produce solutions that are significantly different. The general hypothesis is that the quality of solutions generated from a threshold accepting search process is the same regardless of differences in how the search is conducted.

METHODS

Two hypothetical forests are used to illustrate the differences in outcomes when threshold accepting parameters are adjusted. Both forests are subject to problems where there is a maximization (net discounted revenue) and a minimization (deviations from a target wood flow value) objective. The Lincoln Tract (Bettinger et al., 2017) is a hypothetical coniferous forest located in the western United States. It is composed of 87 stands covering 1,841.5 hectares, although three stands are unavailable for harvest as they represent predominantly riparian areas. The remaining 84 stands encompass 1,788.4 ha. Douglas-fir (*Pseudotsuga menziesii*) is the most dominant tree species within the forest. The time horizon is 30 years, and each of the 6 time periods are 5 years long. Harvests are assumed to occur, for modeling purposes, in the middle of each time period. The volumes are represented in thousand board feet (MBF), a traditional unit of sawtimber in the United States. A harvest target of 13,950 MBF per time period is assumed in the minimization problem, an amount that was estimated based on the Hanzlik formula (Hanzlik, 1922). One management action (final harvest) is modeled, and the minimum final harvest age was assumed to be 35 years. The maximum size of a final harvest area is assumed to be 48.6 ha (legal maximum in Oregon). The green-up period after a final harvest has been scheduled is assumed to be 5 years (one time period).

The Jones Tract is a hypothetical coniferous forest located in the southern United States. It is composed of 81 stands covering 1,053.1 hectares, although 16 stands are unavailable for harvest as they represent predominantly wetland areas. Thus 65 stands of trees are available for harvest activities (867.4 ha). Loblolly pine (*Pinus taeda*) is the most dominant tree species within the forest. The time horizon is 20 years, and the time periods are each 5 years long. Harvests are assumed to occur, for modeling purposes, in the middle of each time period. The volumes are represented in tons (907.2 kg), a traditional unit of weight in the United States. A harvest target of 19,000 tons per time period is assumed in the minimization problem, an amount estimated based on the Meyer amortization method (Meyer, 1952). One management action (final harvest) is modeled, and the minimum final harvest age was assumed to be 22 years. The maximum size of final harvest area is assumed to be 48.6 ha. The green-up period after a final harvest has been scheduled is assumed to be one time period.

Four forest management problems are addressed in this work:

1. Maximize discounted net revenue from final harvests and employ unit restriction harvest adjacency (URM) constraints (Murray, 1999) to control the timing and placement of final harvests
2. Maximize discounted net revenue from final harvests and employ area restriction harvest adjacency (ARM) constraints to control the timing and placement of final harvests
3. Minimize squared deviations between the scheduled harvest volumes in each time period of the time horizon and a target harvest volume and employ a unit restriction harvest adjacency model to control the timing and placement of final harvests
4. Minimize squared deviations between the scheduled harvest volumes in each time period of the time horizon and a target harvest volume and employ an area restriction harvest adjacency model to control the timing and placement of final harvests

Minimizing the squared deviations between scheduled harvest volumes and a target harvest volume leads to a more even scheduled harvest volume across all time periods than simply minimizing the straight differences between scheduled harvest volumes and a target harvest volume. The two objective function values for the management problem formulations are:

$$Maximize \sum_{t=1}^{T} \sum_{n=1}^{N} \left(\frac{x_{tn} r_{tn}}{p} \right) \quad (1)$$

$$Minimize \sum_{t=1}^{T} \left(H_t - TV \right)^2 \quad (2)$$

These problems include an accounting row or function

$$\sum_{n=1}^{N} \left(x_{tn} v_{tn} a_n \right) - H_t = 0 \ \forall \ t \quad (3)$$

And only one (at most) final harvest can be assigned to each stand during the time horizon.

$$\sum_{t=1}^{T} x_{tn} \le 1 \quad \forall n,\ x_{tn} \in \{0,1\} \tag{4}$$

When the unit restriction model of adjacency is assumed, the following constraint applies when a final harvest is applied to a stand (n) during time period t:

$$x_{tn} + \sum_{z=lw}^{uw} \sum_{m \in O_n}^{M} x_{zm} \le 1 \quad \forall n,\ t \tag{5}$$

$$lw = t - (g-1) \tag{6}$$

$$if\ \ lw < 1,\ lw = 1 \tag{7}$$

$$uw = t + (g-1) \tag{8}$$

$$if\ \ uw > T,\ uw = T \tag{9}$$

Here, variable z represents the length of time known as the green-up period. In this case, each stand (n) and each neighboring stand (m) are assessed as a pair, and at most only one of these is scheduled a potential final harvest within the green-up window defined by time period t. When the area restriction model of adjacency is assumed, the following constraint applies:

$$x_{tn} a_n + \sum_{z=lw}^{uw} \sum_{m \in O_n \cup S_n}^{M} x_{zm} a_m \le MA \tag{10}$$

In this case, each stand (m) that is adjacent to the focal stand (n), along with any other management units adjacent to m, and their neighbors, and so on, are assessed as a sprawling cluster of potential final harvest areas all scheduled within the green-up window defined by time period t.

For the maximization problems, the following wood flow constraints apply:

$$\left(\left(\sum_{t=1}^{T} H_t \right) / \ T \right) - AVGV = 0 \tag{11}$$

$$H_t \ge (1-\beta)\ AVGV \quad \forall t \tag{12}$$

$$H_t \le (1+\beta)\ AVGV \quad \forall t \tag{13}$$

where

a_n = area of stand n

$AVGV$ = average scheduled volume across all time periods in the time horizon

β = allowable deviation (decimal percentage, where 25% = 0.25) from average scheduled wood volume

g = green-up window, expressed as number of time periods t

H_t = scheduled harvest volume during time period t

i = interest rate for discounting purposes

lw = the lower limit (time periods) on the period of time within a green-up window of a proposed final harvest

m = a neighboring stand (management unit) to stand n

M = the total number of neighboring stands to stand n

MA = maximum final harvest area size

n = a single timber stand from the model forest

N = the total number of timber stands in the model forest

O_n = the set of neighboring stands to stand n

$$p = (1+i)^{(t-1)*5+(0.5*t)}$$

r_{tn} = potential revenue for scheduling stand n for a final harvest during time period t

S_n = the set of all stands adjacent to stands in set O_n and all stands adjacent to neighbors of neighbors, and so on (Murray, 1999)

t = a single time period

T = the total number of time periods

TV = target harvest volume per time period

uw = the upper limit (time periods) on the period of time within a green-up window of a proposed final harvest

v_{tn} = volume per unit area available for harvest in stand n during time period t

x_{tn} = a binary decision variable indicating whether (1) or not (0) stand n is scheduled for a final harvest during time period t

z = a period of time within a green-up window of a proposed final harvest

The interest rate for discounting purposes (i) is assumed to be 5% in the maximization problem, and timber volumes per time period are allowed to vary (β) by 25% from the average scheduled volume per time period when scheduled.

The maximization problems were subjected to the branch and bound search process within Lingo version 21 (LINDO Systems Inc., 2024). The minimization problems were subjected to quadratic branch and bound search process within Lingo version 21. The threshold accepting heuristic search process, developed using Visual Basic 2012, was employed to generate solutions to these problems. Maximization problems required less than one second to solve with Lingo. Minimization problems, due to the desire to achieve exact even flow, were allowed to run for 50 to 110 hours before the quadratic branch and bound search process was interrupted. Even though the termination point for these searches was unpredictable, we assume the results from these are effective representations of the optimal solution. Heuristic search required about 1 second per instance (run) for the least diligent search and about 10 minutes for the most diligent search.

The general parameters of a threshold accepting search process include:

- Initial threshold value
- Rate of change of the threshold value
- Number of successful moves (iterations of the model) to conduct before changing the threshold value
- Number of unsuccessful moves to attempt before changing the

Table 1. Taxonomy of parameter alternatives used in assessing the threshold accepting heuristic when applied to the Lincoln Tract (maximization and minimization problems) and the Jones Tract (minimization problem).

	Alternative		
	1	2	3
Rate of change	0.99	0.999	0.9999
	(1)	(2)	(3)
Iterations per threshold	1	100	
	(a)	(b)	
Unsuccessful iterations per threshold	500	1000	
	(α)	(β)	
Initial threshold value	1,000,000	3,000,000	5,000,000
	(○)	(●)	(□)

Example: Alternative 1aα○ uses a rate of change of 0.99, 1 iteration per threshold, 500 unsuccessful iterations per threshold, and an initial threshold value of 1,000,000.

threshold value

The latter of these parameters can be based on consecutive or non-consecutive unsuccessful moves since the last time that a successful change was made to the current solution during a search. In the work presented here, it is assumed that the number of consecutive unsuccessful attempts triggers a change in the threshold value. In any event, this element of threshold accepting (changing the threshold due to a large number of unsuccessful attempts to change the current solution) is necessary for the search process to eventually terminate. Unfortunately, this also requires extra coding to track the recognition of unsuccessful attempts (gray boxes in Fig. 1). Methods for utilizing the unsuccessful move strategy were described in Siedentopf (1995). Coulter et al. (2006) also used the unsuccessful count as a way of terminating the search process. The rate of change of the threshold value could either be static (i.e., change the threshold by *X* amount each time), adaptive (e.g., change the threshold value by a variable amount depending on the status of the search through the solution space), or non-linear (e.g., multiply the current threshold value by a rate of change (such as 0.99) to create a new threshold value). In this work, we are assuming that a non-linear rate of change will be employed each time the threshold value is changed. As one might gather, there are an infinite number of combinations of search parameters. Although Pukkala and Heinonen (2006) suggest that the parameters of a threshold accepting heuristic search process might be optimized for specific problems using a Hook and Jeeves direct search approach, here the parameters were selected specifically within certain ranges to illustrate the effect they have on the outcome of the search. And finally, some search processes allow infeasible solutions to a problem to be maintained by penalizing each constraint violation, but for the purposes of the work presented here, it is assumed this is not the course of action chosen.

With each of these four problems noted above, 36 different combinations of threshold accepting parameters are employed. These were selected to represent significant changes in the magnitude of parameter values. For example, for the Lincoln Tract, the initial threshold ranges from 1,000,000 to 5,000,000 US dollars, and the number of iterations per threshold is assumed to be either 1 or 100 (Table 1). For the minimization problems, the objective function value represents squared deviations of scheduled harvest volumes from target harvest volumes, and the initial threshold values vary from 1,000,000 to 5,000,000 units (squared deviations). Since the Jones Tract is smaller than the Lincoln Tract, when maximizing discounted net revenue, the largest value obtainable is around $2,000,000 (US dollars), therefore the initial threshold values when maximization processes are applied to the Jones Tract are 200,000, 350,000, and 500,000 (Table 2). As others have noted (Perea et al., 2008), threshold accepting requires calibration of a number of parameters whose values vary by problem instance. In the work presented here, it is illustrated why calibration might be necessary. Preliminary trials indicated that the initial threshold value for the maximization problems should be between 10 and 25% of the ultimate final objective function value, otherwise relatively small initial threshold values result in a search process much like hill-climbing, and relatively large initial threshold values result in a search process much like random search. In either case, there is a chance that the heuristic search will become stranded on poor quality local optima and be unable to escape to higher quality areas of the solution space.

Each of the four problems noted above were applied to the two model forests, and for each of the 36 sets of threshold accepting parameters assumed, 200 independent runs of the threshold accepting heuristic search process were generated, each producing a feasible forest harvest schedule. In general, 1-opt moves are employed, where one stand is randomly and temporarily selected from the current feasible solution and a change to the harvest timing for that stand is also randomly and temporarily selected. The objective function value and feasibility are then assessed to determine whether the temporary change to the harvest timing of the stand is acceptable. Three enhancements are applied in conjunction with the set of parameter values representative of the most diligent search. The first involves the use of 2-opt moves (Bettinger et al., 1999; Caro et al., 2003), where the harvest timing of two randomly selected stands are temporarily exchanged, after which the objective function value and

Table 2. Taxonomy of parameter alternatives used in assessing the threshold accepting heuristic when applied to the Jones Tract (maximization problem).

	Alternative		
	1	2	3
Rate of change	0.99	0.999	0.9999
	(1)	(2)	(3)
Iterations per threshold	1	100	
	(a)	(b)	
Unsuccessful iterations per threshold	500	1000	
	(α)	(β)	
Initial threshold value	200,000	350,000	500,000
	(○)	(●)	(□)

Example: Alternative 1aα○ uses a rate of change of 0.99, 1 iteration per threshold, 500 unsuccessful iterations per threshold, and an initial threshold value of 200,000.

feasibility are then assessed to determine whether the temporary changes to the harvest timing of the two stands are acceptable. Methods for utilizing 2-opt moves within threshold accepting have been described previously (Nissen and Paul, 1995; Tarantilis and Kiranoudis, 2002; Tarantilis et al., 2004). Since 2-opt exchange moves interject no diversity into the solution (i.e., the number of final harvests per time period remains the same), 1-opt moves need to be intermixed into the search process. Here, we employ a repeating pattern of 50 1-opt moves followed by 10 2-opt moves. The second additional process involves the use of search reversion, which has been shown to be of value in forest harvest scheduling efforts (Bettinger et al., 2015). In search reversion, after a certain number of moves the current solution is replaced by the best solution stored in memory. Here, we assume that search reversion occurs every 50 moves. The third employs both 2-opt moves and search reversion. An additional 200 independent runs were generated each of these three enhancements for each forest / management problem. Thus, for each forest (2) and each management problem (4), 7,800 heuristic search solutions were generated. In total, 62,400 solutions (harvest schedules) were generated by the threshold accepting heuristic search process. These represent a small sample of the potential harvest schedules for the Lincoln Tract (7^{84}) and the Jones (5^{65}), where the population of harvest schedules, whether feasible or not, when using discrete decision variables is

$$\text{Number of different solutions} = \text{Options for each stand}^{\text{Number of stands}}$$

The options for each stand include the choice to employ a final harvest in any period of the time horizon and the choice to not employ a final harvest at all. Thus, there are 7 options for each stand in the Lincoln Tract even though there are only 6 time periods in the time horizon.

As entry into the random number list of the personal computer employed (12th generation Intel® Core™ i9-2900, 2.4 GHz processor and 64 GB RAM) was based on the computer's clock, each of the 200 runs within each set can be considered independent samples from the larger population of potential solutions to the forest management problem (Golden and Alt, 1979; Los and Lardinois, 1982). Statistical tests were therefore conducted in order to assess whether significant differences can be asserted when comparing two sets of objective function values. A set of objective function values is defined by a combination of the forest considered, the management problem applied, and the parameters / processes employed during the search process. The two-tailed Student's *t*-test was applied to assess whether statistically significant differences exist between pairs of sets of solutions, as the distribution of objective function values within each set was approximately normally distributed.

RESULTS

General Results

From the observations of objective function values generated by the heuristic search process, it is obvious that slowing the rate of change in the threshold improves solution values for both the maximization (Fig. 2-5) and the minimization (Fig. 6-9) problems. With each set of three results (e.g., 1aα○, 2aα○, 3aα○) improvements in the median and interquartile range of solution values are evident (i.e., 3aα○ results are better than 2aα○ results, which are better than 1aα○ results). Further, in the far-right side of each figure, the three sets of solution values that represent enhancements upon the most diligent search (3bβ□) generally suggest that these enhancements are necessary to produce a solution near the optimal solution to each problem. In the maximization problems for both the Lincoln and Jones Tracts, it is also evident that sets of solutions generated with 100 iterations per threshold value were generally of higher quality than those which utilized only one iteration per threshold (more clearly evident in the group beginning with 1bα○ and extending to 3bβ□ in Fig. 5). In addition, the interquartile range of these solutions is much smaller than others where only one iteration per threshold was employed. These findings are not as evident with the minimization problem results. Furthermore, when comparing URM and ARM outcomes (e.g., Fig. 4 and Fig. 5), the ARM outcomes have higher quality objective function values due to the added

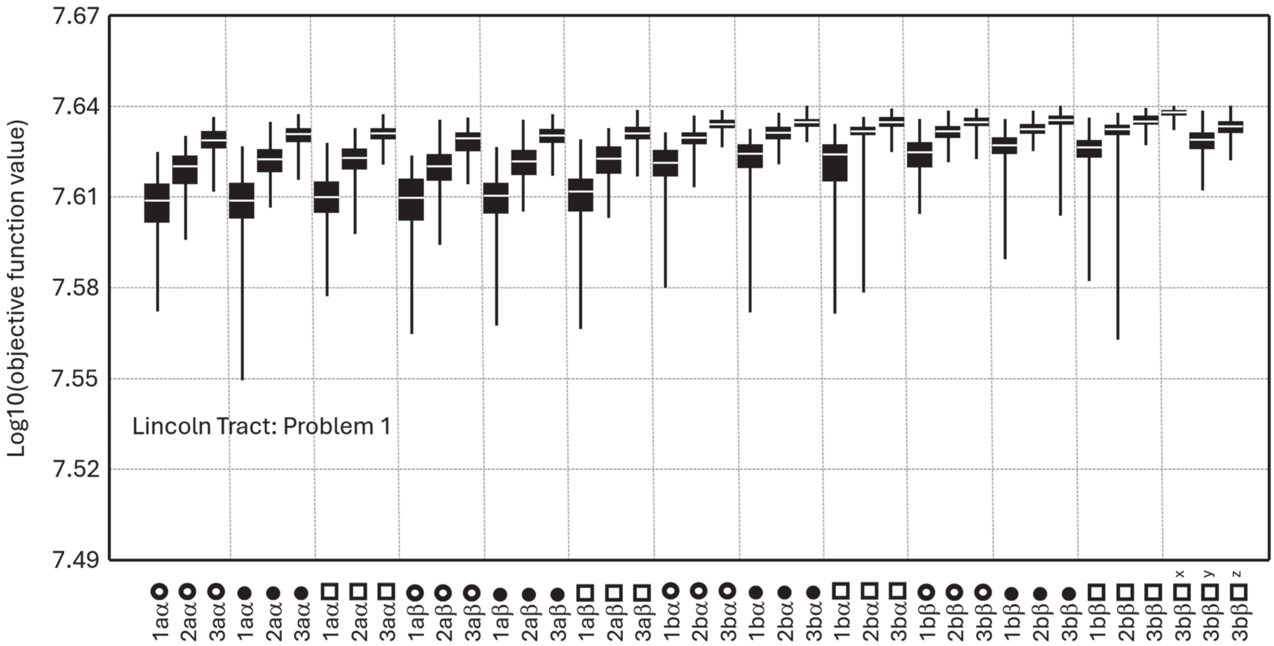

Fig. 2. Box (interquartile range) and whisker (full range) graph illustrating the threshold accepting heuristic search results for the Lincoln Tract and forest management problem 1 (maximization of discounted net revenue and unit restriction adjacency of final harvests). 3bβ□x represents the most diligent search parameters along with 2-opt moves, 3bβ□y represents the most diligent search parameters along with search reversion, and 3bβ□z represents the most diligent search parameters along both 2-opt moves and search reversion.

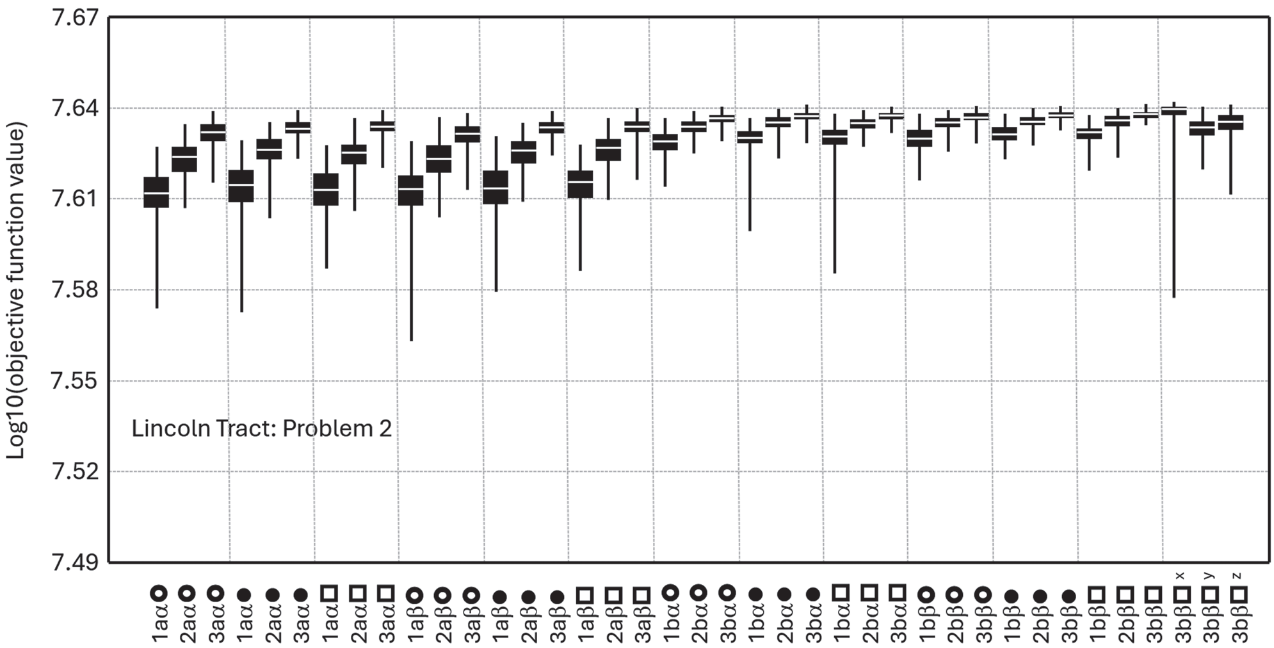

Fig. 3.Box and whisker graph illustrating the threshold accepting heuristic search results for the Lincoln Tract and forest management problem 2 (maximization of discounted net revenue and area restriction adjacency of final harvests). 3bβ□x represents the most diligent search parameters along with 2-opt moves, 3bβ□y represents the most diligent search parameters along with search reversion, and 3bβ□z represents the most diligent search parameters along both 2-opt moves and search reversion.

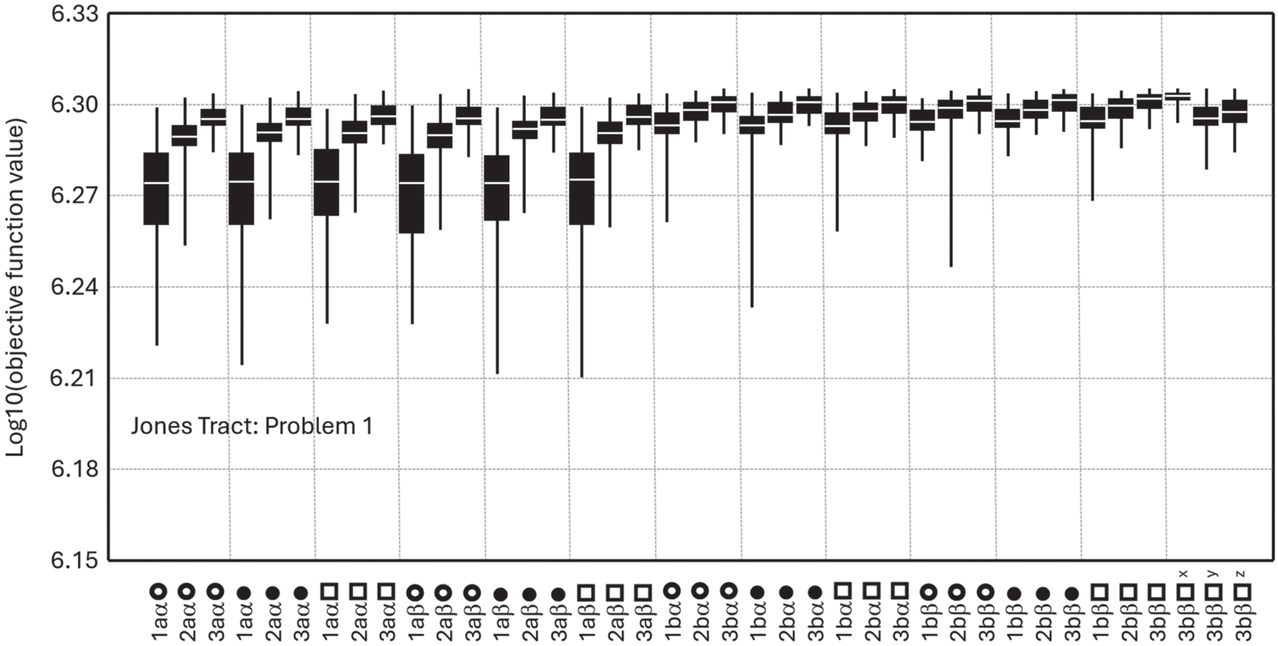

Fig. 4. Box and whisker graph illustrating the threshold accepting heuristic search results for the Jones Tract and forest management problem 1 (maximization of discounted net revenue and unit restriction adjacency of final harvests). 3bβ☐x represents the most diligent search parameters along with 2-opt moves, 3bβ☐y represents the most diligent search parameters along with search reversion, and 3bβ☐z represents the most diligent search parameters along both 2-opt moves and search reversion.

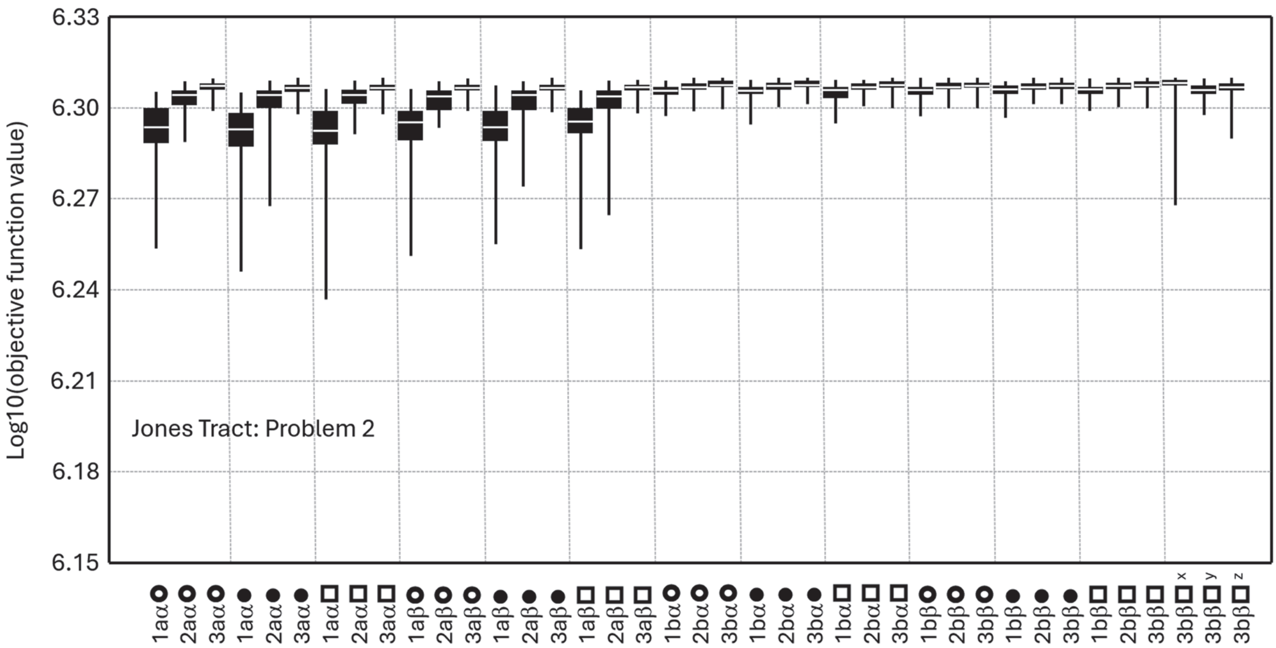

Fig. 5. Box and whisker graph illustrating the threshold accepting heuristic search results for the Jones Tract and forest management problem 2 (maximization of discounted net revenue and area restriction adjacency of final harvests). 3bβ☐x represents the most diligent search parameters along with 2-opt moves, 3bβ☐y represents the most diligent search parameters along with search reversion, and 3bβ☐z represents the most diligent search parameters along both 2-opt moves and search reversion.

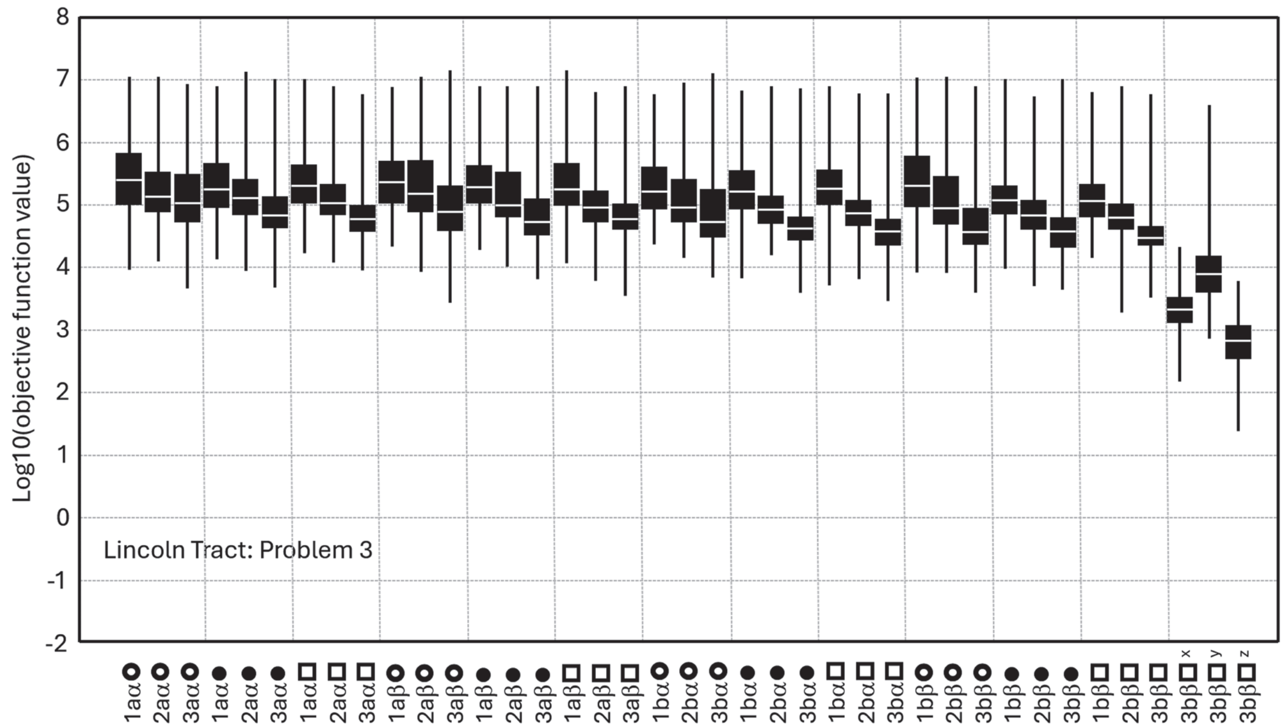

Fig. 6. Box and whisker graph illustrating the threshold accepting heuristic search results for the Lincoln Tract and forest management problem 3 (minimization of discounted net revenue and unit restriction adjacency of final harvests). 3bβ□x represents the most diligent search parameters along with 2-opt moves, 3bβ□y represents the most diligent search parameters along with search reversion, and 3bβ□z represents the most diligent search parameters along both 2-opt moves and search reversion.

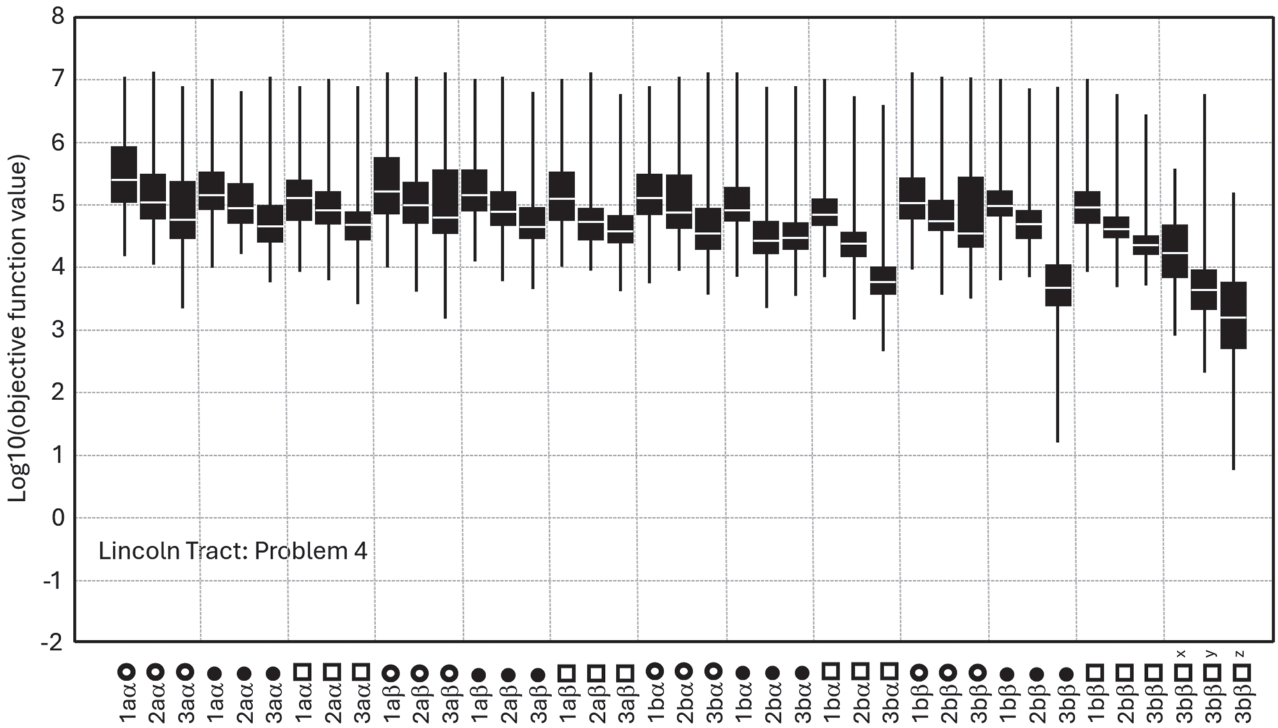

Fig. 7. Box and whisker graph illustrating the threshold accepting heuristic search results for the Lincoln Tract and forest management problem 4 (minimization of discounted net revenue and area restriction adjacency of final harvests). 3bβ□x represents the most diligent search parameters along with 2-opt moves, 3bβ□y represents the most diligent search parameters along with search reversion, and 3bβ□z represents the most diligent search parameters along both 2-opt moves and search reversion.

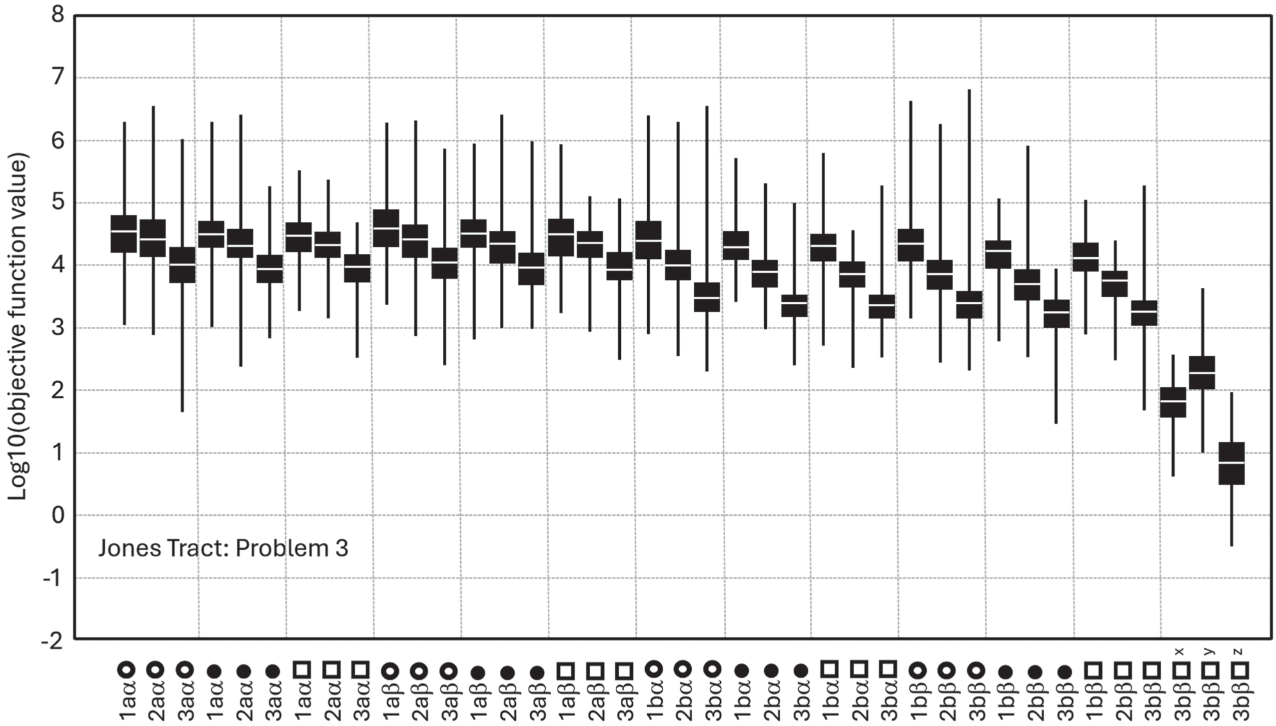

Fig. 8.Box and whisker graph illustrating the threshold accepting heuristic search results for the Jones Tract and forest management problem 3 (minimization of discounted net revenue and unit restriction adjacency of final harvests). 3bβ□x represents the most diligent search parameters along with 2-opt moves, 3bβ□y represents the most diligent search parameters along with search reversion, and 3bβ□z represents the most diligent search parameters along both 2-opt moves and search reversion.

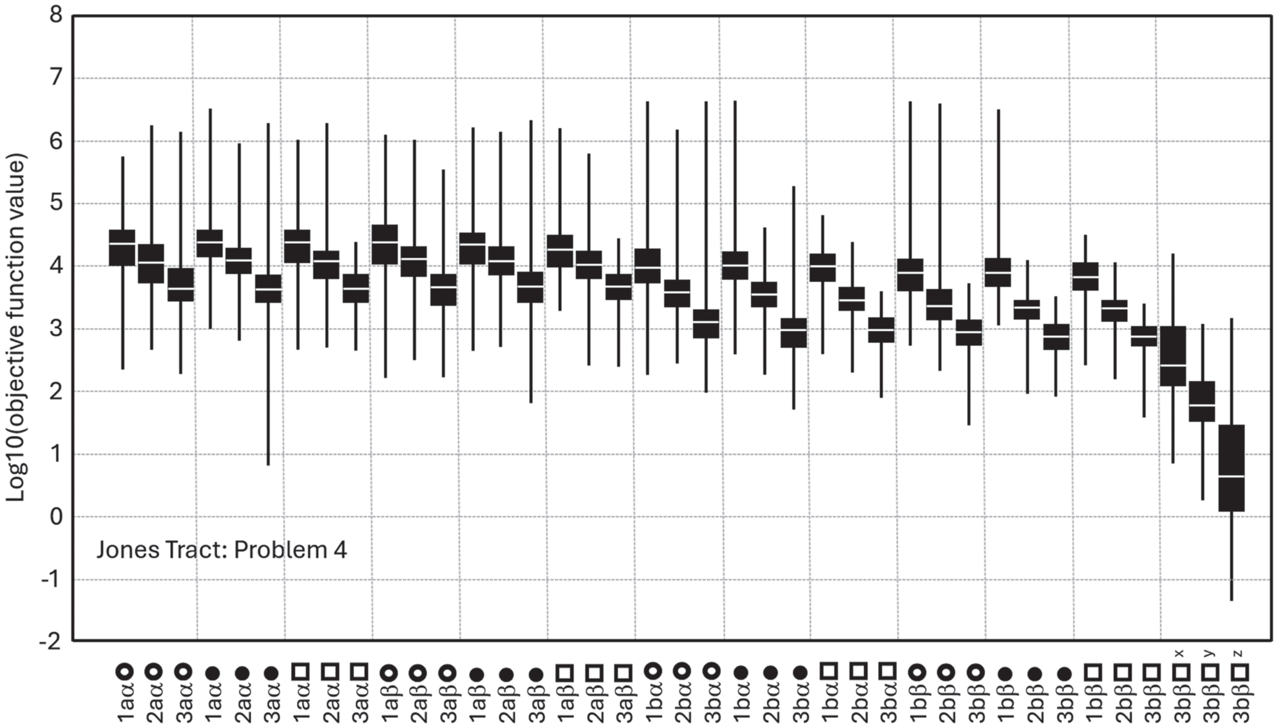

Fig. 9.Box and whisker graph illustrating the threshold accepting heuristic search results for the Jones Tract and forest management problem 4 (minimization of discounted net revenue and area restriction adjacency of final harvests). 3bβ□x represents the most diligent search parameters along with 2-opt moves, 3bβ□y represents the most diligent search parameters along with search reversion, and 3bβ□z represents the most diligent search parameters along both 2-opt moves and search reversion.

Table 3. A comparison of the Lincoln Tract harvest scheduling outcomes from threshold accepting when using parameters that are reflective of the most and least diligent searches.

	Initial threshold value	Rate of threshold change	Successful iterations per threshold	Unsucc. Iterations per threshold	Highest quality solution[a]	Mean quality solution[a]	Lowest quality solution[a]	Coefficient of variation[b]
1. Maximize net revenue / Unit restriction model of final harvest adjacency								
Most diligent (3bβ□)	5,000,000	0.9999	100	1000	43,448,190	43,019,276	42,240,028	0.51
Least diligent (1aα○)	1,000,000	0.99	1	500	42,023,408	40,382,158	37,214,842	2.14
2. Maximize net revenue / Area restriction model of final harvest adjacency								
Most diligent (3bβ□)	5,000,000	0.9999	100	1000	43,831,050	43,460,759	43,123,240	0.34
Least diligent (1aα○)	1,000,000	0.99	1	500	42,433,492	40,927,223	37,530,429	1.97
3. Minimize wood flow deviations / Unit restriction model of final harvest adjacency								
Most diligent (3bβ□)	5,000,000	0.9999	100	1000	3,225	127,118	5,792,699	460.13
Least diligent (1aα○)	1,000,000	0.99	1	500	9,225	795,843	11,226,465	187.54
4. Minimize wood flow deviations / Area restriction model of final harvest adjacency								
Most diligent (3bβ□)	5,000,000	0.9999	100	1000	5,170	173,438	2,800,048	332.77
Least diligent (1aα○)	1,000,000	0.99	1	500	15,544	978,801	11,249,614	186.91

[a] Units are US dollars for the maximization problems and squared deviations of scheduled harvest volumes from a target harvest volume in each time period in the minimization problems
[b] Percent, calculated as (standard deviation / mean) × 100

flexibility the ARM constraint allows in assigning a harvest period to a timber stand. Some other general outcomes include the following:

- With respect to maximization problems (1 and 2) when applied to both case study forests, a relatively large range of final solution values were generally observed when the rate of change in the threshold value was relatively fast (0.99) as compared to slower rates of change.
- With respect to both the minimization and maximization problems (1-4) when applied to both case study forests, repeatable high quality solutions, as reflected in a narrow range of solution values and a relatively short interquartile range, a slow rate of change in the threshold value seems necessary.
- With respect to the minimization problems (3 and 4) when applied to both case study forests, threshold accepting was generally not able to perform well with the search parameters employed without the addition of enhancements (2-opt, reversion, or both).

Increased diligence of the threshold accepting search process is achieved through (a) a higher initial threshold value, (b) a slower rate of change, (c) a greater number of iterations per threshold value, and (d) a greater number of consecutive unsuccessful attempts prior to changing the threshold value. With respect to both forests (the Lincoln Tract and the Jones Tract), the results from employing threshold accepting (Tables 3 and 4) were generally what were expected. The highest quality solutions and the mean quality of solutions were located when using the more diligent search processes. Further, the lowest quality solutions were much worse when using the least diligent search processes than those located using the more diligent search processes. Interestingly, the variation in solution quality was relatively low when solving the two maximization problems, and relatively high when solving the two minimization problems, likely because the better solutions would ideally approach zero (thus the mean is lower) when solving the minimization problems.

When incorporating additional processes to the threshold accepting search process, the quality of the solutions generated generally improved. With the two maximization problems that were applied to Lincoln Tract, adding just 2-opt moves to the search process improved the best solution located even though the mean solution value declined in one of these cases (Table 5). Adding just the reversion process did not seem to improve the results in the two maximization problems, in fact the highest quality solution located, mean solution value, and lowest quality solution located were all lower than when reversion was not employed (simply using the most diligent search process parameters). This suggests that perhaps the search reversion rate employed was not the most appropriate for these problems. Further, with respect to the two maximization problems, when both 2-opt moves and search reversion are employed, an improvement in the highest quality solution was observed over simply using the most diligent search process parameters, yet the results were not as good as simply using 2-opt moves alone. With the two minimization problems, both 2-opt moves and search reversion, when employed separately, dramatically improved the results generated by the threshold search process. When employing both 2-opt moves and search reversion, the highest quality results were obtained.

When 2-opt moves and search reversion were applied to the maximization problems of the Jones Tract (Table 6), we observed that the addition of 2-opt moves improved the highest quality

Table 4. A comparison of the Jones Tract harvest scheduling outcomes from threshold accepting when using parameters that are reflective of the most and least diligent searches.

	Initial threshold value	Rate of threshold change	Successful iterations per threshold	Unsucc. Iterations per threshold	Highest quality solution[a]	Mean quality solution[a]	Lowest quality solution[a]	Coefficient of variation[b]
1. Maximize net revenue / Unit restriction model of final harvest adjacency								
Most diligent (3bβ◻)	500,000	0.9999	100	1000	2,020,051	1,999,527	1,958,518	0.72
Least diligent (1aα○)	200,000	0.99	1	500	2,011,828	1,975,977	1,924,821	0.91
2. Maximize net revenue / Area restriction model of final harvest adjacency								
Most diligent (3bβ◻)	500,000	0.9999	100	1000	2,045,444	2,032,845	1,998,809	0.43
Least diligent (1aα○)	200,000	0.99	1	500	2,022,865	1,958,843	1,795,534	2.61
3. Minimize wood flow deviations / Unit restriction model of final harvest adjacency								
Most diligent (3bβ◻)	5,000,000	0.9999	100	1000	48	2,995	193,019	453.13
Least diligent (1aα○)	1,000,000	0.99	1	500	1,130	104,503	1,982,576	263.70
4. Minimize wood flow deviations / Area restriction model of final harvest adjacency								
Most diligent (3bβ◻)	5,000,000	0.9999	100	1000	37	842	2,469	58.19
Least diligent (1aα○)	1,000,000	0.99	1	500	224	38,968	565,716	171.24

[a] Units are US dollars for the maximization problems and squared deviations of scheduled harvest volumes from a target harvest volume in each time period in the minimization problems
[b] Percent, calculated as (standard deviation / mean) × 100

Table 5. A comparison of the Lincoln Tract harvest scheduling outcomes from threshold accepting when using parameters that are reflective of the most diligent searches and further enhancements.

	Highest quality solution[a]	Mean quality solution[a]	Lowest quality solution[a]	Coefficient of variation[b]
1. Maximize net revenue / Unit restriction model of final harvest adjacency				
Most diligent (3bβ◻)	43,448,190	43,019,276	42,240,028	0.51
Most diligent (3bβ◻) + 2-opt moves[c]	43,552,305	43,288,773	42,723,856	0.31
Most diligent (3bβ◻) + search reversion[d]	43,359,417	42,370,812	40,802,585	1.02
Most diligent (3bβ◻) + 2-opt moves and search reversion[c,d]	43,507,808	42,819,229	41,754,987	0.71
2. Maximize net revenue / Area restriction model of final harvest adjacency				
Most diligent (3bβ◻)	43,831,050	43,460,759	43,123,240	0.34
Most diligent (3bβ◻) + 2-opt moves[c]	43,882,583	42,924,888	37,816,493	3.49
Most diligent (3bβ◻) + search reversion[d]	43,705,603	42,992,724	41,676,410	0.85
Most diligent (3bβ◻) + 2-opt moves and search reversion[c,d]	43,782,704	43,131,960	40,889,511	1.05
3. Minimize wood flow deviations / Unit restriction model of final harvest adjacency				
Most diligent (3bβ◻)	3,225	127,118	5,792,699	460.13
Most diligent (3bβ◻) + 2-opt moves[c]	155	2,607	21,650	83.11
Most diligent (3bβ◻) + search reversion[d]	744	110,949	4,036,578	454.98
Most diligent (3bβ◻) + 2-opt moves and search reversion[c,d]	24	926	5,970	98.59
4. Minimize wood flow deviations / Area restriction model of final harvest adjacency				
Most diligent (3bβ◻)	5,170	173,438	2,800,048	332.77
Most diligent (3bβ◻) + 2-opt moves[c]	825	38,178	384,016	133.21
Most diligent (3bβ◻) + search reversion[d]	202	322,706	5,776,699	356.33
Most diligent (3bβ◻) + 2-opt moves and search reversion[c,d]	6	8,128	156,073	253.06

[a] Units are US dollars for the maximization problems and squared deviations of scheduled harvest volumes from a target harvest volume in each time period in the minimization problems
[b] Percent, calculated as (standard deviation / mean) × 100
[c] For every fifty 1-opt moves, ten 2-opt moves are employed
[d] For every fifty successful iterations, the search reverts back to the best solution stored in memory of the computer

Table 6. A comparison of the Jones Tract harvest scheduling outcomes from threshold accepting when using parameters that are reflective of the most diligent searches and further enhancements.

	Highest quality solution[a]	Mean quality solution[a]	Lowest quality solution[a]	Coefficient of variation[b]
1. Maximize net revenue / Unit restriction model of final harvest adjacency				
Most diligent (3bβ□)	2,020,051	1,999,527	1,958,518	0.72
Most diligent (3bβ□) + 2-opt moves[c]	2,020,051	2,005,953	1,967,365	0.59
Most diligent (3bβ□) + search reversion[d]	2,019,279	1,976,534	1,898,641	1.01
Most diligent (3bβ□) + 2-opt moves and search reversion	2,019,460	1,984,325	1,924,852	1.06
2. Maximize net revenue / Area restriction model of final harvest adjacency				
Most diligent (3bβ□)	2,045,444	2,032,845	1,998,809	0.43
Most diligent (3bβ□) + 2-opt moves[c]	2,045,594	2,022,447	1,857,429	2.06
Most diligent (3bβ□) + search reversion[d]	2,043,983	2,024,873	1,988,226	0.53
Most diligent (3bβ□) + 2-opt moves and search reversion	2,045,581	2,028,689	1,953,502	0.61
3. Minimize wood flow deviations / Unit restriction model of final harvest adjacency				
Most diligent (3bβ□)	48	2,995	193,019	453.13
Most diligent (3bβ□) + 2-opt moves[c]	4	81	373	76.30
Most diligent (3bβ□) + search reversion[d]	10	329	4,253	134.49
Most diligent (3bβ□) + 2-opt moves and search reversion	0[e]	12	93	119.56
4. Minimize wood flow deviations / Area restriction model of final harvest adjacency				
Most diligent (3bβ□)	37	842	2,469	58.19
Most diligent (3bβ□) + 2-opt moves[c]	7	1,128	15,792	183.27
Most diligent (3bβ□) + search reversion[d]	2	121	1,208	138.96
Most diligent (3bβ□) + 2-opt moves and search reversion	0[f]	46	1,467	299.14

[a] Units are US dollars for the maximization problems and squared deviations of scheduled harvest volumes from a target harvest volume in each time period in the minimization problems
[b] Percent, calculated as (standard deviation / mean) × 100
[c] For every fifty 1-opt moves, ten 2-opt moves are employed
[d] For every fifty successful iterations, the search reverts back to the best solution stored in memory of the computer
[e] 0.05
[f] 0.02

solutions located. In general, when either of these additional processes were added to the basic threshold accepting search process, the mean quality of solutions improved. Interestingly, the variation in solution quality was much lower when search reversion was employed compared to simply using the most diligent search process parameters or employing 2-opt moves alone. In the two minimization problems, both 2-opt moves and search reversion, when employed separately, dramatically improved the results generated by the threshold search process. And again, when employing both 2-opt moves and search reversion, the highest quality results were obtained. In fact, the optimal solutions to the two minimization problems were located using the threshold accepting search process supplemented with both 2-opt moves and search reversion.

The mixed integer programming objective function values to the maximization problems applied to the Lincoln Tract were \$43,581,416.80 (URM) and \$43,882,583.90 (ARM). The threshold accepting search process located the ARM optimal solution twice (in 1% of the solutions generated) using 3bβ□ parameters and 2-opt moves employed. The very best threshold accepting solution for the URM problem was \$56,161.80 (0.13%) from the URM optimal solution using 3bα● parameters without the use of 2-opt moves or search reversion. The mixed integer programming objective function values to the maximization problems applied to the Jones Tract were \$2,020,050.97 (URM) and \$2,045,594.00 (ARM). The threshold accepting search process located the URM optimal solution once using 3bβ□ parameters without the enhancement of 2-opt moves or search reversion, and once using 3bβ□ parameters with the enhancement of 2-opt moves. The threshold accepting search process located the ARM optimal solution one time using using 3bβ□ parameters with the enhancement of 2-opt moves. In total, for the maximization problems applied to both case study forests, threshold accepting located the optimal solution 5 times out of 31,200 attempts using the sets of search parameters studied here (0.016% of the solutions generated). However, 47.1% of the solutions generated by threshold accepting were within 1% of the global optimum values for the maximization problems applied to both case study forests.

The mixed integer programming objective function values to the minimization problems applied to the Lincoln Tract were 0.90 (URM) and 0.45 (ARM). The very best threshold accepting solution for the URM problem was 24.0 using 3bβ□ parameters and enhanced with 2-opt moves and search reversion. Similarly, the very best threshold accepting solution for the ARM problem was 5.8 using 3bβ□ parameters and enhanced with 2-opt moves and search reversion. The mixed integer programming objective function values to the minimization problems applied to the Jones Tract were 0.05 (URM) and 0.02 (ARM). The very best threshold accepting solution for the URM problem was 0.32 using 3bβ□ parameters and enhanced with 2-opt moves and search reversion. The threshold accepting search process located the ARM optimal solution one time using using 3bβ□ parameters with the enhancement of 2-opt moves and search reversion. In total, for the minimization problems applied to both case study forests, threshold accepting located the optimal solution 1 time out of 15,600 attempts using the sets of search parameters studied here.

Tests of Significant Differences

Most paired tests of significant differences ($p < 0.05$) amongst sets of outcomes (200 samples per parameter set) indicated that the objective function values of the sets were statistically significantly different, with a few exceptions. From the vast array of paired comparisons amongst two different sets of solutions generated by the threshold accepting heuristic, some general trends were evident.

1. Within a forest management problem, when the heuristic search was applied to either of the two case study forests using (a) the same rate of change in the threshold, (b) the same number of iterations per threshold, and (c) the same number of unsuccessful iterations per threshold, yet the search was initiated from different threshold levels, there were generally no statistically significant differences ($p = 0.05$) in the quality of the objective function values within sets of solutions generated.
2. Within a forest management problem, when the heuristic search was applied to either of the two case study forests using (a) the same initial threshold level, (b) the same rate of change in the threshold, (c) only 1 iteration per threshold, yet a different number of unsuccessful iterations per threshold were assumed (500 or 1000), there were generally no statistically significant differences ($p = 0.05$) in the quality of the objective function values within sets of solutions generated. This was not the case when 100 iterations per threshold were assumed.
3. Within a forest management problem, when the heuristic search was applied to either of the two case study forests using (a) the same initial threshold, (b) the same number of iterations per threshold, (c) the same number of unsuccessful iterations per threshold, yet a different rate of change in the threshold, there were generally statistically significant differences ($p = 0.05$) in the quality of the objective function values within sets of solutions generated.
4. Within a forest management problem, when the heuristic search was applied to either of the two case study forests using (a) the same initial threshold, (b) the same rate of change in the threshold value, (c) the same number of unsuccessful iterations per threshold, yet different iterations per threshold (1 vs. 100), there were generally statistically significant differences ($p = 0.05$) in the quality of the objective function values within sets of solutions generated.
5. Within the maximization problems, when the heuristic search was applied to either of the two case study forests using (a) a moderate rate of change (0.999), (b) different initial threshold levels, (c) different number of unsuccessful iterations per threshold, and (c) where the iterations per threshold was assumed to be 1000, there were generally no statistically significant differences ($p = 0.05$) in the quality of the objective function values when these alternatives were compared with the most diligent searches using 3bβ□ parameters enhanced with 2-opt moves and search reversion. However, generally, statistically significant differences were observed when these sets of solutions were compared to searches using 3bβ□ parameters enhanced with 2-opt moves alone. Furthermore, these findings were not observed in the minimization problems.
6. Within the minimization problems, in nearly all instances of different search parameters, the sets of solutions from the three alternatives that included enhancements (2-opt moves, search reversion) were statistically significant different ($p = 0.05$) with respect to the quality of the objective function values within other 36 sets of solutions generated.

DISCUSSION

When applied to the forest management problems described in this paper, threshold accepting acted as a relatively fast search heuristic. In general, with each run of the heuristic search process there is a hill-climbing phase, an adjustment phase, and a fine-tuning or steady-state phase (Fig. 10) (Bettinger et al., 1997). However, specific search parameters can affect the amount of time needed to complete the search process. For example, there seemed to be a 10-fold increase in the amount of time required as the assumed rate of change increased in magnitude. When the rate of change of the threshold value was 0.99, the general amount of time required to complete the search process was about 6 seconds per run. As the rate of change increased to 0.999, about one minute per run was required, and as the rate of change increased to 0.9999 about 10 minutes per run were required. It is acknowledged that these observations of performance can improve had the search process been coded in another computer language or enabled on a computer with faster CPU speed. The speed at which exact methods solved the maximization problems suggests that for forest harvest scheduling cases where the adjacency constraints can easily be developed and the wood flow constraints are not too narrow, this may be the more appealing option. When there may be difficulty in developing adjacency constraints (particularly in ARM problems with multiple time period green-up assumptions) or when there is a desire for very narrow wood flow deviations from period to period, the

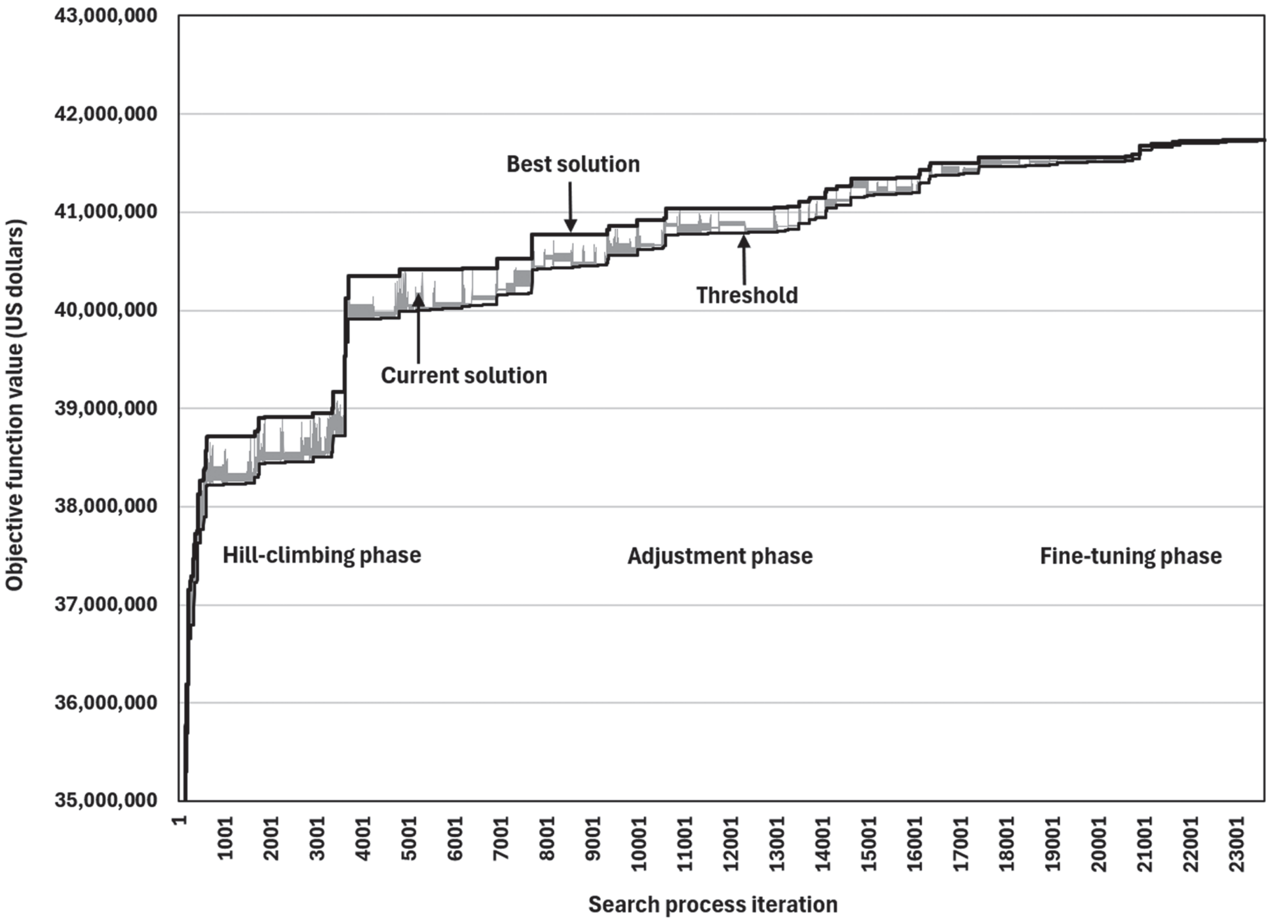

Fig. 10.General behavior of the threshold accepting heuristic search process when it is applied to the Lincoln Tract and forest management problem 1 (maximization of discounted net revenue and unit restriction adjacency of final harvests).

heuristic search process may be the more appealing option. The reason, for example, that the minimization problems required an extensive amount of time when branch and bound methods were employed was the desire for a harvest schedule that contained no deviation in the wood flow from period to period.

Although a large number of heuristic search solutions were developed for this research effort, we could have explored different assumptions regarding the implementation of 2-opt moves and we could have explored different assumptions regarding the search reversion rate (as has been shown in Bettinger et al. (2015)). Should these activities eventually be pursued, the most appropriate combination of 1-opt and 2-opt moves might be assessed, along with the most appropriate search reversion rate. We hypothesize that the most appropriate of these options, in combination with the normal heuristic search parameters, may be problem-specific. Since the intent of this research effort was to illustrate the general quality of solutions generated by the threshold accepting heuristic search process as parameter values are altered, a deeper analysis of enhancements is left open for future research efforts.

While the optimal solution to several of the problems investigated here was located, Winkler and Fang (1997) noted that beyond some acceptable amount of computing effort, further increases in the number of iterations of local search algorithms generally will not improve the overall quality of solutions produced. And so, the hope of locating higher quality solutions may be just that (wishful thinking) when using parameter sets that are unable to allow a diligent search through a solution space. Enhancements such as those described here (2-opt moves and search reversion) that are embedded in s-metaheuristic search processes may overcome some of these difficulties (Bettinger and Boston, 2017). Further, slowing the rate of change of the threshold value or increasing the number of consecutive unsuccessful moves needed before changing the threshold value both act to increase the number of iterations of this search process. To be consistent with the thoughts of Winkler and Fang (1997) all sets of solutions less than the most diligent search would seem to not employ an acceptable amount of computing effort as the most diligent searches led to improved objective function values.

There are other methods for adjusting the manner in which threshold accepting conducts a search. For example, Lin et al. (1995) described how the search might be limited to only promising areas of the solution space, rather than consideration of all random moves from the current solution to the proposed solution. The reversion process that is described in this work is similar and serves to also limit the search to promising areas of the solution space. Further, Lin et al. (1995) described methods for adapting the threshold value based on recent search performance, allowing the threshold to not only decrease as the search progresses, but also to increase again when many local minima and maxima are recognized during a short period of search time. This form of adjustment to the acceptance criteria is similar in concept to what might be employed in a demon algorithm (Creutz, 1983; Wood and Downs, 1998), which is a *s*-metaheuristic that utilizes an acceptance rule that varies in magnitude depending on recent search history. Other means for adjusting a search process have been investigated, for example, Nissen and Paul (1995) suggested increasing the number of iterations allowed as the threshold declines, since the ability to locate improved solutions and escape from local optima may be more difficult when the threshold value decreases. Further, Frausto-Solis et al. (2021) suggested a form of a ruin and recreate process (as they note, a *chaos* perturbation) to re-start a threshold accepting search process from a different place in the solution space. Even further, Dhouib et al. (2010) suggested that to diversity a search, one might add memory to the search process, through the use of a tabu state assigned only to moves that lead to a lower quality objective function value. These opportunities to perhaps improve the manner in which a threshold accepting search process addresses a forest harvest scheduling problem are left to others to pursue.

As a final statement on the usefulness of a threshold accepting in forest harvest scheduling efforts, both Zhu and Bettinger (2008) and Li et al. (2010) have suggested that this form of *s*-metaheuristic search process could be combined with a different form of *s*-metaheuristic search process (tabu search) to improve the quality of forest harvest schedules that have wood flow and harvest adjacency constraints. In these cases, a threshold accepting search process may be beneficial for the initial hill-climbing phase of the search due to the speed at which the process moves an initial randomly developed (and poor quality) forest harvest schedule to a moderately well-valued schedule. A tabu search heuristic could then the employed upon the best solution provided by threshold accepting to adjust and refine the quality of the harvest schedule. As tabu search needs to assess a number of potential neighboring solutions during each iteration of the model prior to selecting one, it is effectively much slower in operation than threshold accepting. Yet the value of adding tabu search may be in the deterministic nature that it employs to adjust and refine the threshold accepting solution. As the potential value of the combined metaheuristic approach has been described in both Zhu and Bettinger (2008) and Li et al. (2010), and since this research effort focuses simply on the behavior of threshold accepting, readers are encouraged to visit the other works to understand more fully the value of the combined approach.

CONCLUSIONS

From the analysis provided in this research effort it is evident that high quality solutions to forest harvest scheduling problems can be produced as a threshold accepting heuristic search process more diligently navigates through the solution space. This diligence involves allowing higher amounts of unsuccessful attempts allowed before the threshold value changes, a slower rate of change in the threshold value, the use of 2-opt moves to navigate through the neighborhood, and periodic reversion to the best solution held in memory to intensify the search in high quality areas of the solution space. Significant differences in the quality of the forest harvest schedules developed using threshold accepting, as reflected by the objective function values, were observed when the number of iterations per threshold varied and when the rate of change in the threshold value varied. Although the number of unsuccessful iterations per threshold and the initial threshold level are important assumptions for the heuristic search process, in certain cases, no significant differences in solution quality were observed when these varied. As a general rule, particularly when wood flow deviations are narrow (as in the minimization problem investigated here), enhancements to threshold accepting (2-opt moves and search reversion) resulted in higher quality forest harvest scheduling solutions when used in conjunction with the search parameters that represented the most diligent search.

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Article

Automated Topographic Correction Using the Google Earth Engine

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ABSTRACT

This study developed a way to automate the topographic correction process, specifically the C and SCS+C methods, using the Google Earth Engine (GEE) as a platform. We developed a script that enables users to specify the target path and row, period of acquisition, and the Normalized Difference Vegetation Index (NDVI) threshold required for correction. Then the desired topographic correction is realized based on these inputs. The data to be corrected were obtained from Landsat 8. Users were required to prepare a limited number of parameters to execute code on the GEE correctly; these included the Landsat path, row, image-acquisition period, country name of the largescale international boundary polygons, the NDVI threshold used for the regression analysis, and the center latitude and longitude of the display screen. The NDVI and slope angle obtained from a digital elevation model were used to define the area to be sampled and to obtain the parameters required for the correction model automatically. It was immediately apparent that shadows were removed from the corrected image compared to the uncorrected image. After comparing the correlation coefficients before and after correction for each band, the corrected values were substantially lower than the uncorrected values, indicating that the correction was made appropriately. The code proposed here requires little extra effort to implement, even when both the C and SCS+C correction methods are applied.

keywords: code, C method, SCS+C method, Google Earth Engine, topographic correction

INTRODUCTION

During satellite observations of the Earth's surface, the effects of the atmosphere and topography on the resulting images are unavoidable. Changes in apparent spectral reflectance due to shading caused by the ruggedness of terrain are known as topographic effects, and are recognized as a key challenge that limits the practical utilization of satellite data. In areas with complex topography, these effects are significant, and variations in lighting conditions due to rugged terrain cause differences in the observed data that are unrelated to vegetation conditions. Topographic effects impact forest damage assessment (Ekstrand, 1996), the attributes of forest stand structure (Cohen and Spies 1992), and landcover classification (Fahsi et al., 2000, Vanonckelen et al., 2013). Several correction methods have been developed to mitigate the impact of topographic effects on observed data (Dong et al., 2020).

Such correction can be broadly classified into non-geometric and geometric methods (Murakami, 2007). Non-geometric methods are typically simple models that require no data other than satellite imagery and corrections are made based on band-to-band ratios or other factors (Ekstrand, 1996). Geometric methods use a digital elevation model (DEM) to incorporate the angle of incidence and reflection of sunlight on the ground surface into the correction. As one of the methods that considers geometric variation, the non-Lambertian model uses empirical parameters to correct each band, resulting in highly accurate corrections (Sola et al., 2016).

However, the complexity of differences in solar altitude and topographic relief makes it difficult to devise a definitive method to evaluate the adequacy of correction. To address this issue, Sola et al., (2016) conducted a multi-criteria evaluation of several correction methods. Their study used seven different criteria to evaluate 10 correction methods: the C (Teillet et al., 1982), Smoothed C-Correction (Riaño et al., 2003), SCS+C (Soenen et al. 2005), Statistical-Empirical (Teillet et al., 1982), Minneart (Minnaert, 1941), Enhanced Minneart (Smith et al., 1980), Pixel-based Minneart (Ge et al., 2008), Modified Minnaert (Richter, 1998), two stage normalization (Civco, 1989), and slope-matching (Nichol et al., 2006) methods.

Currently, there is no software or service that can perform the necessary processing for topographic correction in a single

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step. As a result, achieving topographic correction often involves combining multiple processes within the geographic information system (GIS) software, which can increase the required manual effort and time investment. In particular, calculation of empirical parameters for non-Lambertian models is complicated (Murakami, 2007) and cannot be completed by GIS software alone. The use of multiple software packages is therefore required to accomplish the necessary calculations and parameter estimations. In addition, the use of commercial software for topographic correction often necessitates a valid license, which can be an additional cost. Because topographic correction can be computationally intensive, the processing time can be significantly increased when working with computers with inadequate capability. Another challenge arises when multiple images need to be corrected simultaneously. Currently, there is no efficient way to process all of the images in a batch or in a parallel manner, resulting in a multiplicative increase in the required man-hours. Because topographic correction is a pre-processing step to remove topographic effects from satellite imagery prior to its use in research, the process should ideally be performed easily and with little effort on the part of the user.

These problems can be solved using the Google Earth Engine (GEE), which is a cloud computing platform designed to process and store data at a petabyte scale (Mutanga and Kumar 2019). The most important feature of this system is its ability to streamline the entire process, from data search to analysis and the display of results, all of which are conducted on a cloud server. This eliminates the need for users to search for, download, and manage data individually when conducting their analysis (Kobayashi 2018). For analysis, the suggested approach is to use a code editor, which is a web-based integrated development environment. This allows users to create and edit appropriate scripts using JavaScript or Python notation. Scripts can be written with any combination of processes, such as those used in GIS software, so that all of the processes necessary for correction can be written at once. Therefore, once a script is created, the second and subsequent processes can be performed simply by pressing the RUN button. In addition, the GEE does not require the purchase of a license. It is free to Google account holders and can be used for noncommercial purposes without charge.

We automated topographic correction using the GEE as a platform, specifically the C and SCS+C methods. We developed a script in which the user specifies the target path and row, period of acquisition, and the Normalized Difference Vegetation Index (NDVI) threshold required for correction. Then the desired topographic correction is realized based on these inputs. Verification of accuracy was performed to evaluate the acceptability of the correction.

METHODS

The GEE

Data provided by the GEE can be obtained from the Data Catalog (https://developers.google.com/earth-engine/datasets). Each dataset listed in the Data Catalog contains the source, supplementary information, and a description of the data. The data can be used by writing the script described in the Earth Engine Snippet on the code editor. All data used in this study were obtained from the Data Catalog.

Satellite Data

Landsat 8 was the source of the data to be corrected. The collection 2, level 2, and Tier 1 products were selected. The United States Geological Survey (USGS) implemented a data management category called "collection" to organize the Landsat archive starting from 2016. The reorganization of Collection 1 involved modifying the file names and metadata structure to ensure consistent quality over time and across devices. In Collection 2, there were further changes in the preprocessing of the data and improvements in data access and distribution performance (USGS, 2020). "Level" expresses the level of processing applied to the data. In level 1, the processing is aimed at improving geometric and radiometric accuracy, while in level 2 atmospheric correction is applied in addition to the level 1 processing. "Tier" is another indicator of data quality. The three Tier categories are real-time (RT), Tier 1 (T1), and Tier 2 (T2), with RT provided immediately after observations, Tier 1 for the highest quality data available, and T2 for data that are not usually of normal quality, such as nighttime or cloud data (USGS, 2022).

In the GEE scripting environment, when working with collection data, it is common to select multiple images at once based on specific criteria. Therefore, in this study, as a criterion for selecting images to be corrected, those with the smallest percentage of clouds during the period specified by the user were selected. Potential uses of the corrected images include forest-type classification and monitoring of changes in forests. Among the Landsat 8 bands, the visible, near-infrared, and shortwave infrared regions are particularly suitable for such applications (Vogelmann et al. 2009; Davies et al. 2016). Therefore, band 2 through band 7 were extracted from the acquired data and corrected. The path and row of an image were found on the USGS website (https://landsat.usgs.gov/landsat_acq#convertPathRow).

Largescale International Boundary Polygons (LSIB2017) Dataset

The LSIB2017 is a polygon dataset provided by the Office of the Geographer and Global Issues at the U.S. Department of State that represents land areas by country. These data were used to clip (cut-out) the uncorrected images and DEMs to reduce the processing load for the correction. This did not include ocean area data that were not subject to correction.

DEMs

The DEMs used in the study were generated by the Shuttle Radar Topography Mission (SRTM). Several types of SRTM-derived DEMs are provided by the GEE but we used the "NASA SRTM Digital Elevation 30 m," provided by the USGS. This DEM is a joint effort of the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence

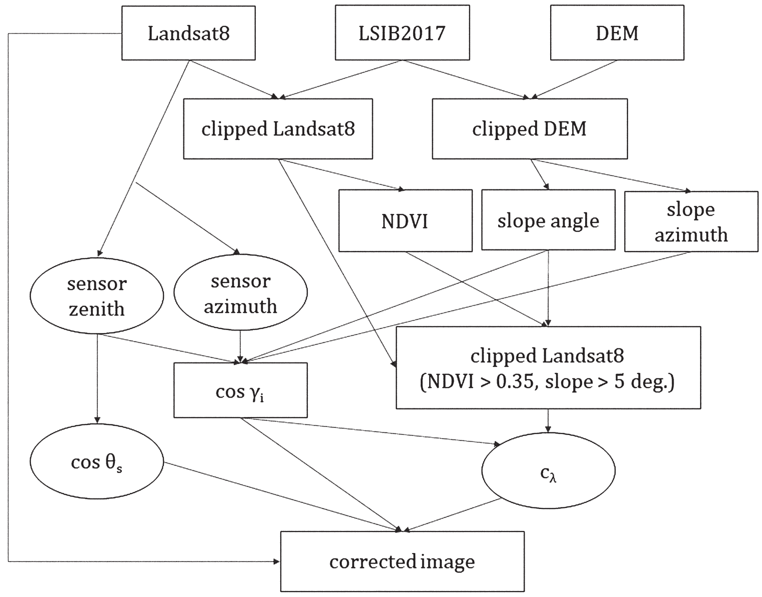

Fig. 1. Flowchart of C method.

Agency (NGA), with the participation of the German Aerospace Center (DLR) and the Italian Space Agency (ISA) (USGS, 2015). The resolution of the data is 30 m.

Correction Methods

The C and SCS+C methods were selected to correct for topographic effects. The C method, developed by Teillet et al. (1982), incorporates empirical parameters into the equation to resolve overcorrection in the case of large angles of incidence in the COS method (Smith et al., 1980). SCS+C, developed by Soenen et al. (2005), incorporates empirical parameters similar to the C method to resolve the deficiencies of the SCS method (Gu and Gillespie, 1998) but is prone to overcorrection. The COS, SCS, C, and SCS+C methods are shown in equations (1)–(4), respectively.

$$L_{corr,\lambda} = L_\lambda \frac{\cos\theta_s}{\cos\gamma_i} \tag{1}$$

$$L_{corr,\lambda} = L_\lambda \frac{\cos s \cos\theta_s}{\cos\gamma_i} \tag{2}$$

$$L_{corr,\lambda} = L_\lambda \frac{\cos\theta_s + C_\lambda}{\cos\gamma_i + C_\lambda} \tag{3}$$

$$L_{corr,\lambda} = L_\lambda \frac{\cos s \cos\theta_s + C_\lambda}{\cos\gamma_i + C_\lambda} \tag{4}$$

where $L_{corr,\lambda}$ is the corrected digital number (DN), L_λ is the original DN, θ_s is the solar zenith angle, γ_i is the solar incidence angle, C_λ is the empirical parameter (intercept and slope were obtained from a regression analysis of the cosine of the solar incidence angle and uncorrected DN value), and s is the slope angle.

The solar zenith angle was calculated by subtracting the solar altitude obtained from Landsat metadata from 90 degrees. Empirical parameters were calculated for each band and were derived by calculating the intercept and slope from a regression analysis of the cosine of the solar incidence angle and the uncorrected DN value. To restrict the target area to forested areas, a regression analysis was conducted by extracting pixels with an NDVI of more than 0.35 and a slope angle of more than 5 degrees. The solar incidence angle is the angle between the solar rays and the Earth's surface and is defined by four factors: the slope angle of the terrain, the azimuth angle, the solar zenith angle, and the solar azimuth angle. The solar incidence angle was calculated as follows:

$$\cos\gamma_i = \cos\theta s \cos s + \sin\theta s \sin s \cos(a - a') \tag{5}$$

where a is the slope azimuth and a' is the solar azimuth. Solar azimuth angles were obtained from Landsat metadata. The slope angle and slope azimuth were created from the DEM, and the values were converted from degrees into radians. Flowcharts of the correction are shown in Figures 1 and 2.

Verification

There is no widely established method to verify the efficiency of topographic correction. Here, we used the variation in the correlation coefficient (Gao et al., 2014) and the p-value obtained from the cosine of the solar incidence angle and the DN value of each band, which have generally been used in the past. First, 1000 pixels were randomly selected for each of the images before and after correction, for which the NDVI was 0.35 and the slope angle was greater than 5 degrees. Then, to exclude noisy data, pixels with DN values in the top 5% and bottom 5% of each band were excluded (i.e., 900 points remained). Correlation co-

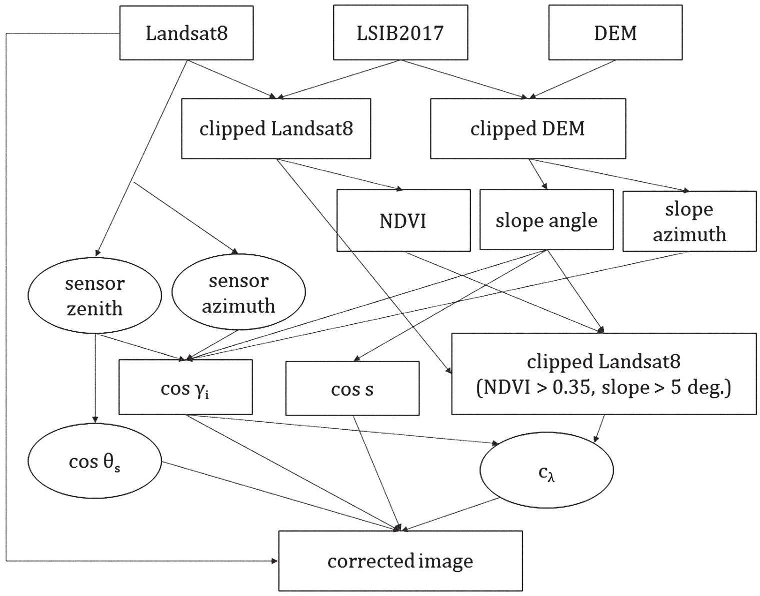

Fig. 2. Flowchart of SCS+C method.

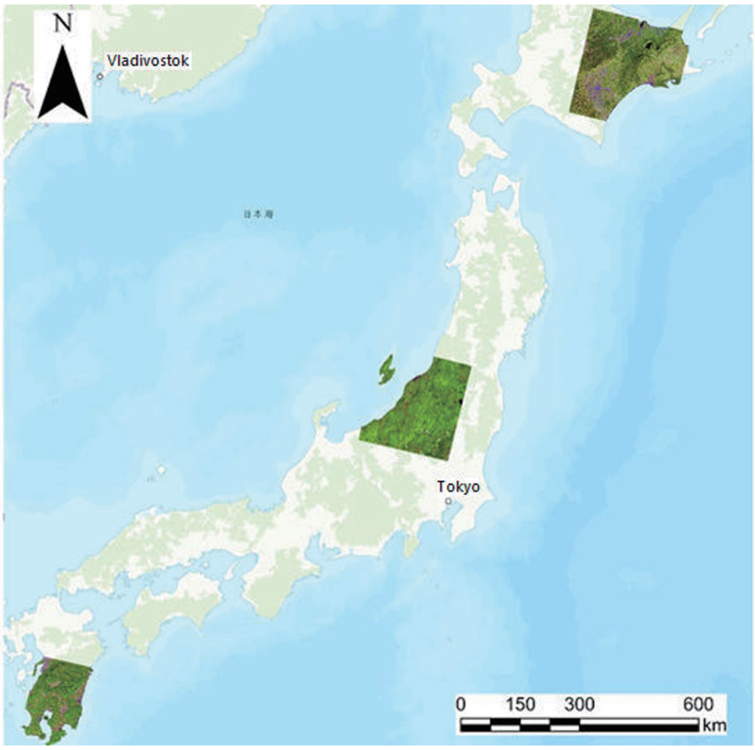

Fig. 3. Images and locations used for accuracy verification.

efficients and p-values were calculated from the DN values and cosine values of the solar incidence angles for these 900 points. In the uncorrected image there was a positive correlation, and if the correction was performed correctly, the correlation was expected to be smaller in the corrected image than in the uncorrected image.

Three areas of Japan with different latitudes and longitudes were selected as target sites for verification (Figure 3). The acquisition period for the validation images was from January 1, 2020, to December 31, 2020, and each selected image was the one with the lowest cloud cover during that period.

RESULTS

Creation of Scripts

The source code created for this study is shown in the Appendix. The Landsat path, row, image acquisition period, coun-

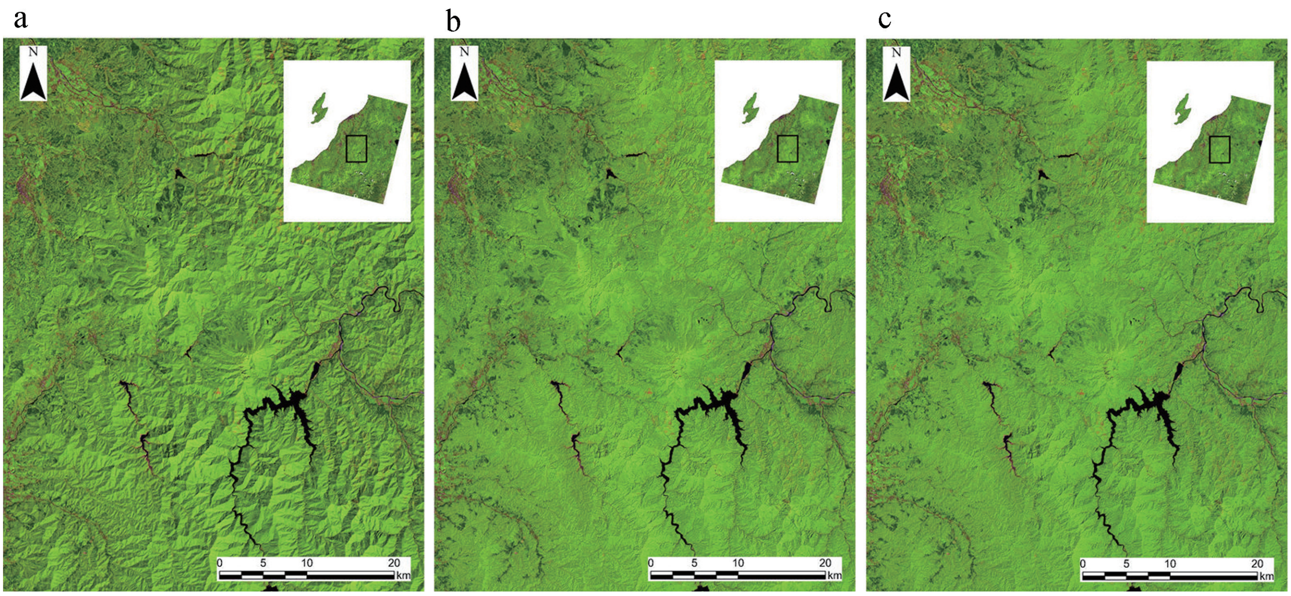

Fig. 4. A zoomed-in view of a part of the uncorrected image, path108 and row34 (Sea of Japan side of Honshu). Acquired on August 26, 2020. R:G:B = band6:band5:band4. (a) uncorrected, (b) C method, (c) SCS+C method.

try name of the LSIB, NDVI threshold used for the regression analysis, and the center latitude and longitude of the display screen were set as variables at the beginning of the code. Even users who do not have a complete understanding of the code's intricacies can make corrections. When exporting the corrected image, the commented-out part at the end of the code was redisplayed and a geometry was created around the target image on the map. Then pressing the RUN button created a new task in the task tab at the top of the screen, and the download task could be executed.

In the Appendix, Part A consists of a "test" function that was independently created. When working with the GEE two methods are required, t (variable name) and console.log (variable name), to display the output results on the map and metadata in the console, respectively. Therefore, we created a test function that combines all of these processes into a single function, and when set to test (variable name), the metadata and output results are displayed simultaneously. Part B presents a function that computes the empirical parameters and applies the correction model to the uncorrected image. To calculate the empirical parameters for each band, a loop process with "for" minutes was not used in this case. Instead, an array was created containing the names of each band (referred to as "useBand" in the script), and a higher-order function called "map()." This was based on Functional Programming Concepts (https://developers.google.com/earth-engine/tutorials/tutorial_js_03) in the GEE Guide. Part C provides the detailed settings for displaying the output results on the map. Here, the minimum and maximum values were set to 7000 and 32000, respectively, for image stretching, but this is only an example. If the corrected image is too dark or too white, the user can adjust the color to a more appropriate tone by setting the range in the Layer Manager to 100%.

Comparison of Images Before and After Correction

Figure 4 shows the images that were used to verify accuracy before and after correction. The images are color composites with Band 6 (SWIR1) assigned to R, Band 5 (NIR) to G, and Band 4 (RED) to B. Comparing the uncorrected and corrected images, it is apparent that shadows have been removed from the latter. Comparing the C and SCS+C methods for each image, few differences can be visually observed.

Verification of Correction

The scatter plots of DN values and the cosine values of the solar incidence angles that were used to calculate the correlation coefficients are shown in Figure 5. The calculated correlation coefficients and p-values are shown in Figure 6. The corrected values are much lower than the uncorrected values, indicating that the correction was appropriate. This is particularly apparent in path 108 and row 34, where all corrected values are less than 0.1, and in path 106 and row 30, where all values are less than 0.1 for bands 4, 6, and 7.

Comparing the correlation coefficients of the C and SCS+C methods, the C method had smaller values for the path 106 and row 30 images, except in band 7. In the path 108 and row 34 images, the SCS+C method had smaller values for bands 2 and 4, but the C method had smaller values for the other bands. In the images of path 112 and row 37, all bands had smaller values for the SCS+C method.

To analyze variations in the correction effect based on slope azimuth, the nine images to be evaluated were first masked using threshold values of NDVI (0.35) and slope angle (5 degrees). Subsequently, these masked images were divided into groups based on 30-degree intervals of slope azimuth, and the median value of each group was calculated. The results are shown in

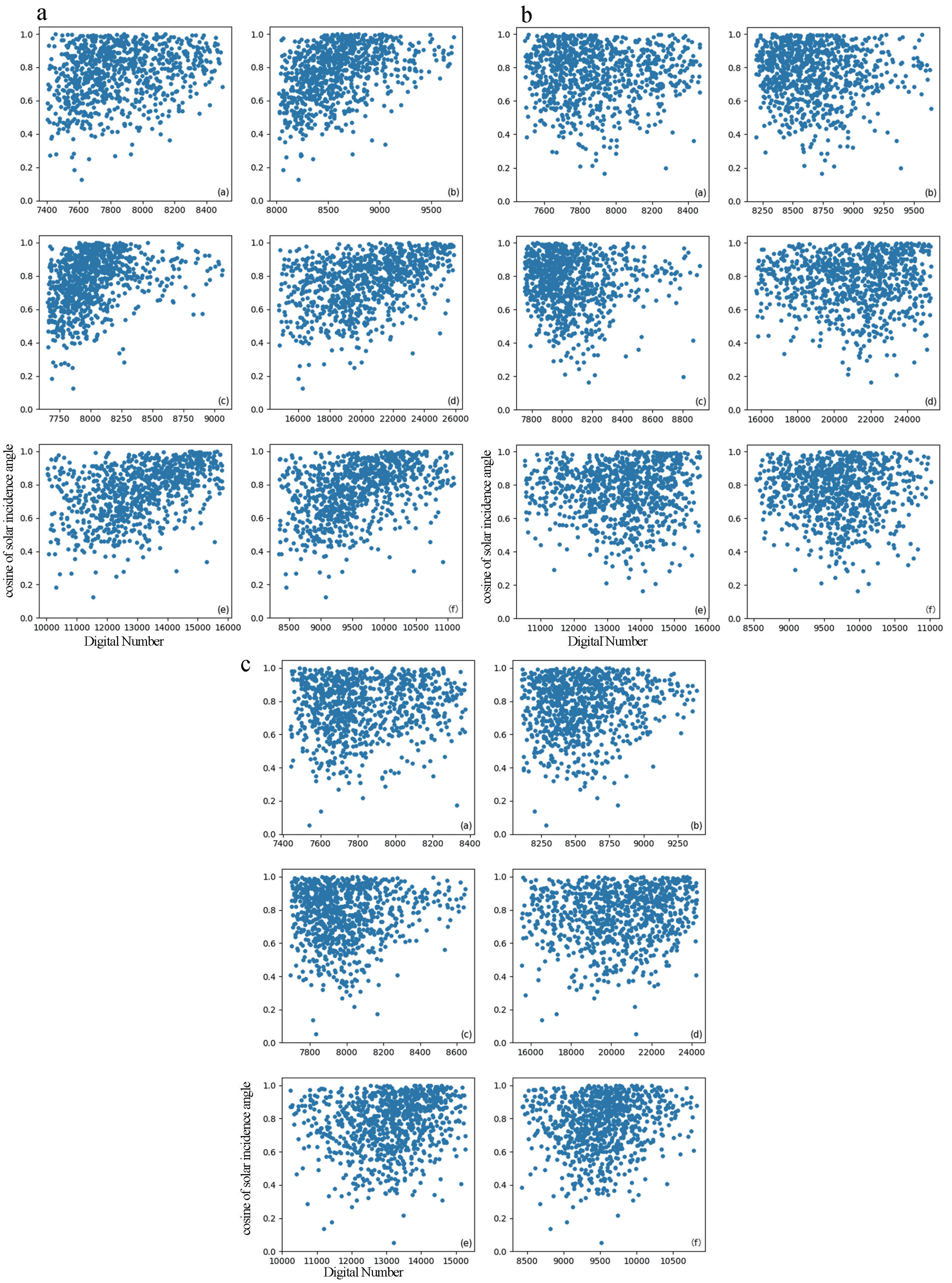

Fig. 5. Scatter plots of DN and cosine values of solar incidence angle used for accuracy verification. Acquired on August 26, 2020. Bands 2 to 7. (a) uncorrected, (b) C method, (c) SCS+C method.

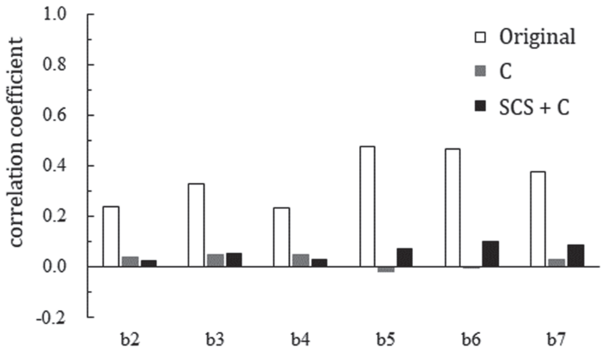

Fig. 6. Correlation coefficients between DN per band and cosine values of solar incidence angle for areas with NDVI > 0.35 and slope > 5°.

Figure 7. Prior to the correction, there was noticeable variation in median values across different slope azimuths, particularly for bands 5 and 6. However, in the corrected image, the median difference decreased, and the fold line flattened. There were no substantial differences in bands 2, 3, 4, and 7 compared to bands 5 and 6 before the correction. However, after the correction, the median difference was smaller and there was little difference between sunny and shaded slopes.

DISCUSSION

Relevance of Correction

The results confirm that the correction was appropriate for both methods. The visual assessment results show that shading caused by topographic ruggedness was substantially reduced in the corrected data (Figure 4). The correlation between DN values and the cosine values of solar incidence angles, which existed before correction, was no longer significant after correction (Figures 5 and 6). The variation in DN values according to slope orientation was also virtually unobservable after the correction (Figure 7). These results confirm that the correction model developed using the GEE worked effectively.

These corrections can be performed using only a few parameters. The user has no need to download data, nor is any complicated preprocessing required. Moreover, only a short time is required to obtain the results, which is a significant improvement compared to the time taken for conventional topographic corrections. This has all been made possible through the existence of the GEE itself, but the code developed here adds considerable value.

The correction scripts created in this study will need to be modified as technology develops. For example, Landsat 9 data are available from 2022, and when using the script created in this study to make corrections to Landsat 9 images, it will be necessary to modify the data loading and metadata access. However, even in this case, only a portion of the script will need to be changed, and no modification to the fundamental algorithm will be required.

Comparison of the C and SCS+C Methods

As shown in Figures 4 and 5, the values of the correlation coefficients after correction varied from image to image and band to band. This variable was dependent on the time of year the image was acquired and the ruggedness of the topography (Park et al., 2017). Therefore, after applying either correction method, the degree of correction should be visually evaluated, and the image with the better correction should be used. The method

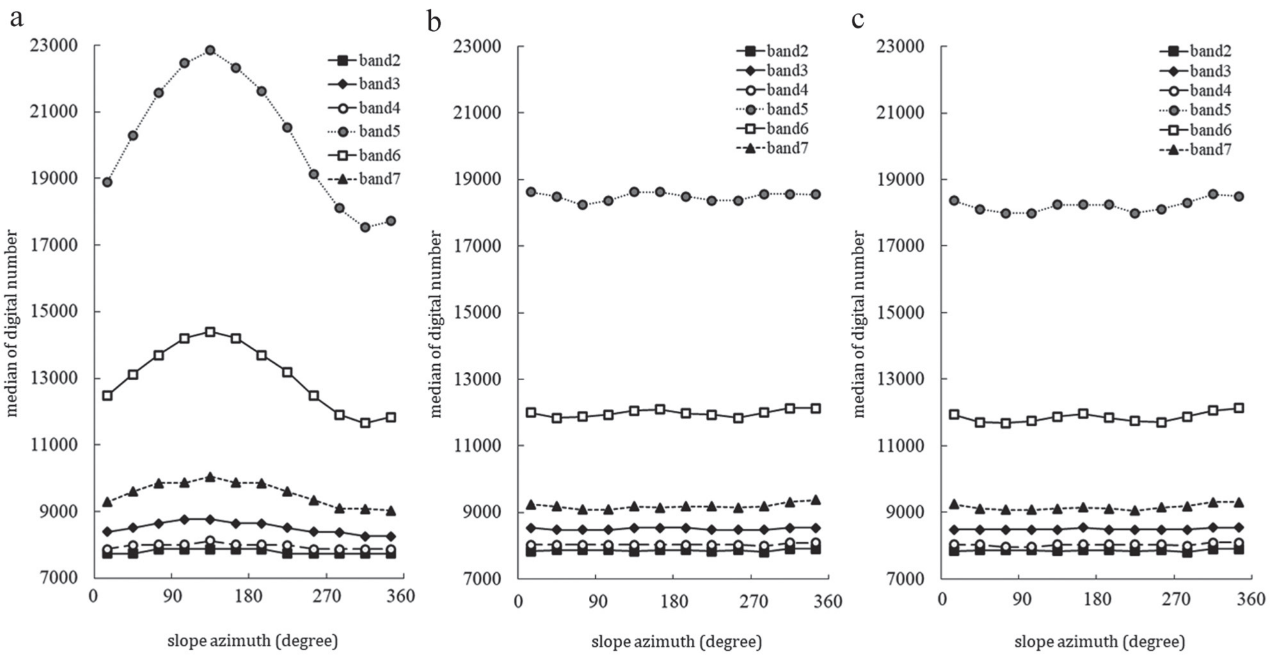

Fig. 7. Relationship between slope azimuth and median DN. The solar azimuth is 139 degrees. path108 and row34 (Sea of Japan side of Honshu). Acquired on August 26, 2020. a) uncorrected, (b) C method, (c) SCS+C method.

proposed here requires little extra effort, even if both correction methods are applied. The additional time required to apply both methods is almost negligible, and therefore there is no reason for users not to use both correction methods.

The NDVI and Slope Angle Thresholds

In an ideal scenario, the NDVI threshold should be determined automatically based on the characteristics of the image. However, there are currently no objective criteria for automatic NDVI thresholding in this method. The appropriate NDVI threshold can vary depending on factors such as vegetation type and the time of year when the image is captured. Because of this and the difficulty in automatically calculating a suitable threshold value, it is recommended that the user performs the correction process and manually searches for an appropriate NDVI threshold by comparing the results obtained. This is why the NDVI threshold is declared at the beginning of the script as a user-settable variable.

As an application of the method using correlation coefficients described here, one possible approach could involve combining multiple steps into a single script. This script would perform the correction process for each NDVI threshold value, ranging from 0 to 1 in increments of 0.1. After correction, the correlation coefficient for each band would be calculated, and these values would be averaged to identify the image with the correlation coefficient closest to 0. However, because processing within a single file can be complex, it is still desirable for users to determine their own threshold values and make corrections.

The slope angle threshold was set at a fixed value of 5 degrees (0.0872 in radians) in the script because the slope angle did not vary significantly across different target images. However, due to the characteristics of the DEM, there are cases when pixels that appear to be vegetated areas in urban areas or cultivated land, as well as mountainous areas, are extracted. However, these inherently undesirable pixels have little effect on the correction. Once extracted based on the threshold value, the pixels are converted into vector data (polygons) and used to clip the satellite image. By setting the minimum scale to 250 m when converting to this vector, most of the pixels in cultivated areas and urban vegetated areas are removed. In this way, apparent micro-slopes are largely excluded.

CONCLUSIONS

We developed a method for automating topographic-effect correction, as well as scripts for the C and SCS+C methods. Using the GEE cloud computing platform as the automation platform, users can easily make corrections. The code, together with a readme file, is available on GitHub. Users can automatically achieve correction with minimal parameter preparation. Using the the GEE, users can obtain corrected images without preparing any data, including those for the DEM.

Compared to general analysis software, the GEE is more difficult to operate intuitively and requires basic programming knowledge. However, it also has many benefits, such as high processing performance due to the process being executed in a cloud environment, and no license is required for use; once a script is created, similar processing can be easily performed a second time and thereafter, and there is no time-consuming data-acquisition process. Examples of GEE applications include detecting disturbances in tropical seasonal forests (Shimizu et al. 2019) and its use in the forest change point extraction program (FAMOST), which is being developed by the Forestry Agency (Japan Forest Technology Association, 2022). The FAMOST program uses an NDVI value derived from the optical satellite imagery of two periods to extract changes in forests, such as clearcuts. By superimposing the information on the extracted change points with geospatial information obtained from local governments, the system can be used for a wide range of tasks, such as checking the status of logging based on a logging-notification system, early detection of illegal logging, checking the location of forest land development, and checking the occurrence of disasters (Forestry Agency 2021). False extraction is inevitable in automatic change extraction, and the shading caused by topographic effects is often the cause. If the correction method developed in this paper were incorporated into FAMOST, we expect that it would substantially reduce false extraction results.

The 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines propose the gain-loss method and the stock change method for analyzing changes in the forest carbon stock, and the stock change method, which considers the change in carbon stock at two points in time as emissions and sinks. This is the most widely applied method in many countries (Hirata et al. 2012). A combination of remote sensing and field surveys has been found to be effective for determining the amount of change in carbon stock at the national level (UN Climate Change, 2007). Studies have estimated carbon stocks using remote sensing with topographic correction (Clerici et al.. 2016; Dabi et al., 2021), and the effectiveness of correction has been widely discussed. Therefore, it is expected that the correction script developed in this study can be used to estimate changes in carbon stocks with noise-reduced data.

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Short communication

Forest Cover Changes in the Lungga River Basin of Guadalcanal, Solomon Islands

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ABSTRACT

Forest monitoring is of great importance for effective forest conservation and management. Changes in forest cover around the Lungga River, Guadalcanal, Solomon Islands, were identified by visual interpretation using the web-mapping service. Four satellite images from Google Earth Pro 7.3 taken in 2014 (April 10), 2016 (September 30), 2018 (July 29), and 2023 (April 22) were used to detect deforestation areas around the river, within a 50 m buffer zone. Deforestation was defined as the conversion of forest land to other land uses. As a result, for the first time, we've been able to show detailed changes in forest cover over 10 years in Guadalcanal, the Solomon Islands, although the area covered is limited. During the period, up to 10% of the forest in the surveyed area had been removed. Although land cover has been gradually recovering with shrubs and grasses within a few years after deforestation, it is a slow process, and the forest will not be able to return to its original pristine state. Increasing population, food security, and economic development are considered the main causes of deforestation on the Solomon Island. Continuous forest monitoring will be necessary in the future for forest conservation and management. Remote sensing and GIS will make a major contribution to this. It would be prudent to prioritize the development of human resources having these skills.

Keywords: Deforestation, GIS, Satellite images, Visual interpretation, web-mapping service

INTRODUCTION

Deforestation is a significant global issue. FAO (2020) reports that 420 million ha of forest have been lost since 1990. Degradation and excessive removal of forests have contributed to water supply depletion, soil erosion, food insecurity, and loss of wildlife habitat (Evans et al., 2018). In particular, tropical countries had the highest net forest loss and deforestation rate, with an average annual deforestation rate of 11.7 million ha/yr over a 30-year period. The earth's tropical rainforests are under the greatest threat, whether from livestock grazing in South America or the expansion of croplands such as oil palm plantations in Asia (FAO, 2022).

Forest monitoring is of great importance for the effective forest conservation and management. Consequently, forest monitoring has been carried out at the global, national, regional, and local levels (Hansen et al., 2013; Goetz et al., 2015; FAO, 2022). However, in some countries and regions, forest monitoring is not adequately conducted due to limitations in human and financial resources (Katovai et al., 2015). The Solomon Islands, the subject of this study, is one such country where forest monitoring is inadequate (Katovai et al., 2015) despite the fact that forests cover 80% of the country's land area (Ministry of Forestry and Research, 2024).

It is helpful that relatively simple and inexpensive monitoring strategies can be implemented in countries with limited financial and human resources to facilitate the accumulation of detailed data on changes that can then be used for forest conservation and management purposes. The visual interpretation of the web-mapping service such as aerial images on Google Earth Pro represents a relatively simple and cost-effective approach to acquiring land cover data (e.g. Taylor and Lovell, 2012; Pulighe and Lupia, 2016; Srivastava and Chinnasamy 2021). Taylor and Lovell (2012) actually succeeded in the detection of land use and land cover changes combining Google Earth Pro and GIS considering the advantages of the manual classification of the high-resolution satellite imagery for a fine-scale study area.

The purpose of this study is to identify forest cover changes around the Lungga River, Guadalcanal, Solomon Islands, using a relatively simple and inexpensive method of visual interpretation using the web-mapping service.

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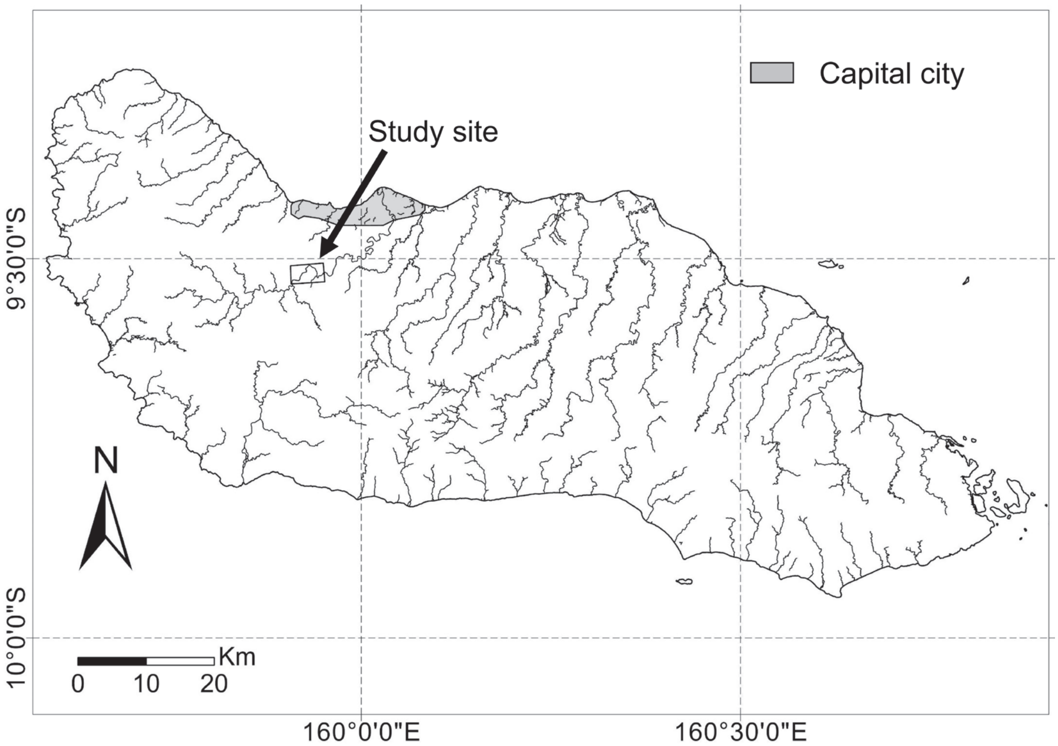

Fig. 1. Study site at Guadalcanal, Solomon Islands. It was located in the middle reaches of the Lungga River. The areas within the 50m buffer zones on both sides of the Lungga River within the rectangular area were surveyed.

MATERIALS AND METHODS

Study Site

The study area is located on both sides of the Lungga River in Guadalcanal, Solomon Islands (9°37′ S, 160°11′ E). The area within the 50m buffer zones on both sides of the Lungga River in the rectangular area in Figure 1 was surveyed. The Lungga River is the longest river on the Solomon Islands with a catchment area of 377 km^2 (FAO, 2016). It starts high in the mountains and empties into Iron Bottom Sound, passing close to the capital of Honiara and Honiara International Airport. The study area was located on the middle reaches of the Lungga River, and the forest type is classified under lowland rainforest below 200 m above sea level (Solomon Islands Government, 2019b). The dominant tree species for timber production in lowland forests are *Campnosperma brevipetiolata, Dillenia salomonensis, Endospermum medullosum, Parinari salomonensis, Terminalia calamansanai, Schizomeria serrata, Maranthes corymbosa, Pometia pinnata, Gmelina moluccana, Elaeocarpus sphaericus and Vitex cofasus* (Solomon Islands Government, 2024). The annual rainfall of the Solomon Islands is 3,000–5,500 mm (Britannica, 2011; Solomon Islands Government, 2017). According to the Solomon Islands Code of Logging Practice (Solomon Islands Government, 2002; Solomon Islands Government and SPREP, 2021), logging is prohibited in some sensitive areas due to erosion risk or ecological importance (e.g., around rivers, on steep topography, and in higher-elevation forests), around villages, and near important ecological areas (e.g., ocean lagoon, lake, and mangroves). The Solomon Islands are located in one of the rainiest regions in the world (Britannica, 2011; Solomon Islands Government, 2017), and cutting down of trees near rivers has a major impact on downstream areas (Albert et al., 2021). Heavy rainfall causes severe erosion in such areas, resulting in downstream impacts such as siltation, flooding, isolation, and submergence of communities (Pattanayak and Wendland, 2007). Deforestation also affects drinking water quality (Wenger et al., 2018). Therefore, the focus of our analysis was on the forest cover change area around the rivers.

Data

Four satellite images from Google Earth Pro 7.3 taken in 2014 (April 10), 2016 (September 30), 2018 (July 29), and 2023 (April 22) were used to detect deforestation areas around the river. The study period 2014–2023 was selected, as a clear Google Earth image before 2014 was unavailable.

Visual interpretation for detecting deforestation areas

The area where the water surface and riparian area could be confirmed by visual interpretation was traced and converted into polygons using the polygon creation function in Google Earth Pro 7.3. The water surface and riparian area were recorded as a single unit. Gravelly and sandy sediment piles can be seen on both banks of the river, and they were almost white in color and easily distinguishable from other land cover. Because these areas

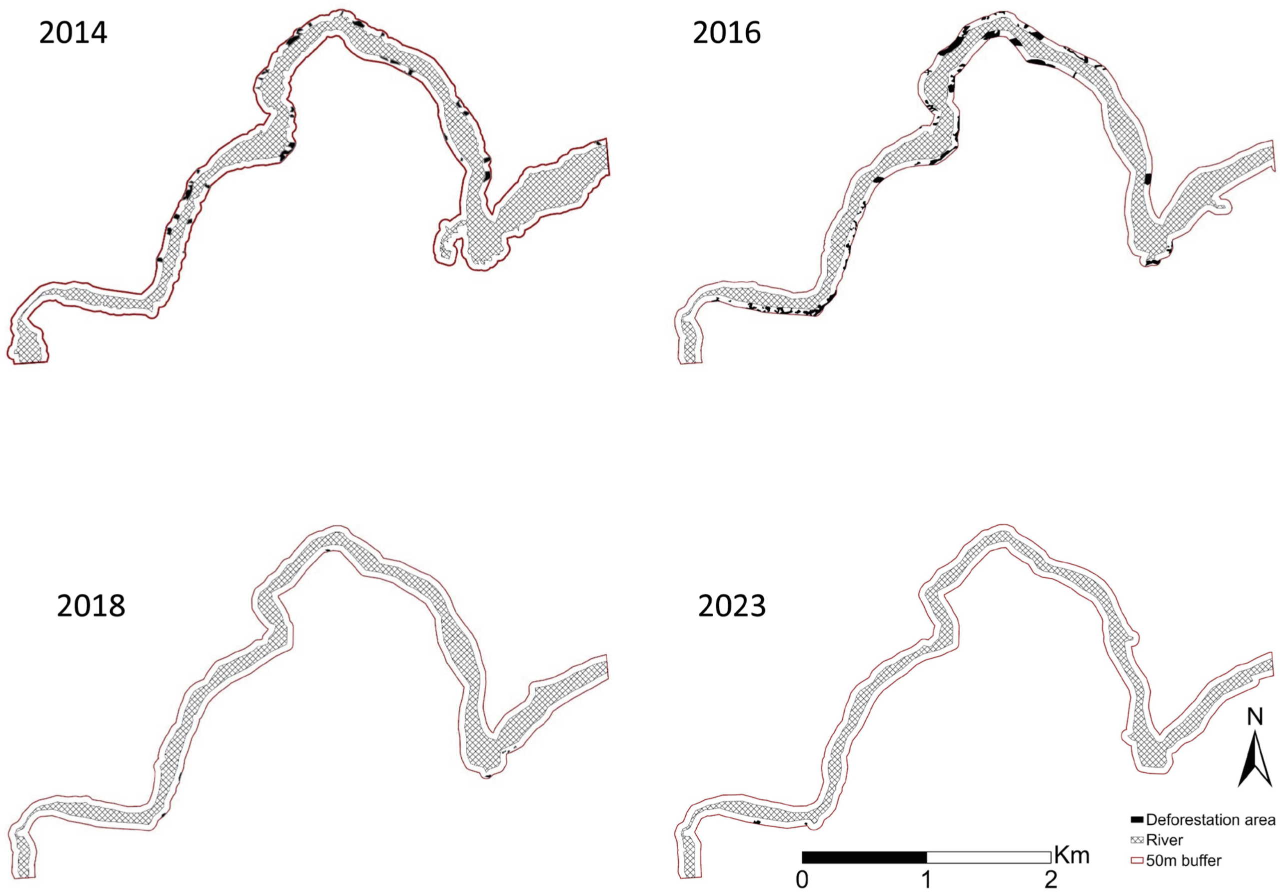

Fig. 2. Detected deforestation area in the 50 m buffer of Lungga River. Deforested areas between 2014 and 2023 were detected by visual interpretation using satellite images from Google Earth Pro 7.3.

were different each year, they were identified and recorded using images from each year. These "river polygons" as river were imported into ArcGIS Pro 3.2.2 (ESRI) and 50 m buffers were created around them to focus on forest cover changes around the rivers. The conservation and management of riparian forests is essential to secure the Solomon Islands' water supply (Solomon Islands Government, 2002; Solomon Islands Government and SPREP, 2021).

The buffers were imported into Google Earth Pro 7.3, and the deforestation area within these buffer zones on both sides of the river was visually interpreted and traced as polygons using the polygon creation function of Google Earth Pro 7.3. Generally, brown soil, red-yellow soil, red clay, and brown loam are widely distributed in mountainous areas (Agricultural Development Consultants Association, 1996) in Guadalcanal. Therefore, when the forest cover is removed, reddish-brown soils appear. We defined "deforestation polygons" as areas that were covered with forest and other vegetation in the previous year's image and showed reddish-brown soil in the following year's image. Although the removal of forest cover can be due to anthropogenic such as logging and natural causes such as flooding, it was difficult to distinguish between the two in this study. The FAO also defines deforestation as the conversion of forest land to other land uses, whether or not caused by human activities. These "deforestation polygons" as deforestation areas were imported into ArcGIS Pro 3.2.2 and their areas were calculated.

RESULTS

Figure 2 shows the detected deforestation areas in each year within the 50m buffer around the river. In 2014 and 2016, there was active deforestation on both sides of the river. In 2016, 10% of the forest in the study area was removed. Since 2018, there have been little forest cover changes. In the earlier images, deforestation areas were visible, but in the more recent images, there were areas covered by vegetation with no tree canopy. Although the vegetation has started to recover, as of 2023, these areas still lack large trees. Table 1 lists the river, buffer zone, and deforestation areas for each year. The size of the river area varied significantly by erosion and deposition, decreasing during the study period. It was about 1.6 times smaller in 2023 than in 2014. As a result, the location of the 50m buffer zone that was set based on the river area was also changed for each year. The deforestation area within the 50m buffer has been decreasing since its peak in 2016 (89,351m^2) to 1,286m^2 by 2023.

Table 1. Areas of rivers, buffer zones, and deforestation sites in 2014, 2016, 2018, and 2023.

Year	River area(m^2)	50m buffer zone(m^2)	Deforestation area in buffer zone (m^2) (Area percentage is in parentheses)
2014	1,000,871	906,725	45,754 (5.1%)
2016	872,948	838,598	89,351 (10.7%)
2018	795,457	819,555	3,236 (0.4%)
2023	639,187	827,503	1,286 (0.2%)

DISCUSSION AND CONCLUSION

For the first time, we've been able to show detailed changes in forest cover over 10 years in Guadalcanal, the Solomon Islands, although the area covered is limited to 50 m buffer around the river. The area of deforestation within the area decreased during the study period. Thus, although land cover has been gradually recovering with shrubs and grasses within a few years after deforestation, it is a slow process, and the forest will not be able to return to its original pristine state. In fact, Katovai et al., (2016, 2021) reported that although the trees were covered by a canopy there within 10 years after logging, their original conditions did not recover even after 30 to 50 years in the Solomon Islands in field surveys. Also, considering that reforestation is not common, it may take decades for even secondary forests to become well-established. Tropical rainforests have thin and poor soils, and it is generally difficult to restore natural vegetation after logging (Hayward et al., 2021; Katovai et al., 2015). The width of the river had decreased since the first year of analysis, and the location of the buffer zone changed slightly accordingly. However, since deforestation itself decreased during the study period, and there was almost no deforestation in the surrounding area, the change in the buffer zone is unlikely to have had a significant impact on the extraction of the deforested area.

Solomon Islands Government (2019a) mentioned that increasing population, food security, and economic development are the main causes of deforestation in the Solomon Islands. In fact, the total population of Guadalcanal Island was 109,382 in 1999 and 283,591 in 2019. It has increased 2.6 times in 20 years (Solomon Islands National Statistics Office, 2023). The population is particularly concentrated in the capital, Honiara City of Solomon Islands on Guadalcanal Island, near the coast, where about half of the population (129,569) lived in 2019. The population has increased 2.6 times from 49,107 in 1999. The capital region continues to expand with the construction of industrial, residential, and other important infrastructures into the surrounding forest (Solomon Islands Government, 2019a; Ministry of Lands, Housing and Survey, 2018). Some of the people who have spilled over from the coastal areas of the capital have also been seen building illegal homes in the forests (Ministry of Lands, Housing and Survey, 2018). Excessive commercial logging also exacerbates this problem. The economy of this country has historically been reliant on the export of timber. The government has traditionally relied on the forest industry as a primary source of revenue, with the sector contributing 20% of GDP and 70% of export revenue. The Solomon Islands lost 147,000 ha of primary forest from 2002 to 2023 (Global Forest Watch, 2024). In tandem with this, the log export volume in the Solomon Islands has increased nearly seven-fold from 2001 to 2017 (509,400 m^3 to 3,402,339 m^3 respectively, Solomon Islands Government, 2019a). Our study site was located in a forest remote from the capital city. Given the absence of subsequent construction, it can be inferred that the deforestation was undertaken for the purpose of timber production. Katovai et al. (2015) highlighted those areas without settlements usually demarcated for logging concession within tribal land.

The Solomon Islands are located in one of the rainiest regions in the world (Britannica, 2011; Solomon Islands Government, 2017). As the study site was located in a 50m buffer zone from the river, it cannot be excluded that the deforestation was caused by flooding. In fact, flooding also occurred in Guadalcanal during our study period, which was in 2014 (World Bank, 2021), 2018 (Radio New Zealand, 2018), and 2023 (National Disaster Council, 2023). The annual precipitation was around 2000mm each year (Australian Government, 2024). However, during the study period, the width of the river decreased, as did the area of new deforestation, suggesting that the floods had little effect on deforestation. Moreover, if the soil is deeply removed, as in a flood, the recovery of vegetation, especially woody species, is very slow due to soil infertility (Flores et al., 2020; Manghwar et al., 2024; Marks et al., 2020). In contrast, in the case of deforestation by logging, shrubs might grow within a year (Magnusson et al., 1999; Fredericksen and Mostacedo, 2000). Shrubs were also observed at the deforestation site in this study area, suggesting deforestation due to logging.

We applied visual interpretation for satellite images on Google Earth Pro 7.3. Because we analyzed a small area in this study, we were able to visually interpret deforested areas with a little effort. However, for frequent monitoring of large forests, it is necessary to automate the process of detecting deforested areas from images such as satellite images taken over a wide area. While this has hitherto required advanced knowledge and expensive tools for image analysis, in recent times, free satellite image analysis tools such as Google Earth Engine have become available to the general public with minimal prior knowledge (Brovelli et al., 2020; Mujetahid et al., 2023). It has been difficult to secure the personnel and tools to use these technologies in the Solomon Islands. However, it is possible that deforestation will persist, and climate change is contributing to the occurrence of frequent heavy rains that result in flooding. It would be prudent to prioritize the development of these human resources.

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Journal of Forest Planning is a peer-reviewed periodical that publishes articles, reviews, and short communications. It covers all aspects of forest management, modeling, and assessment such as forest inventory, growth and yield modeling, remote sensing and geospatial information technologies for forest management, forest management planning, forest zoning, evaluation of ecosystem services, managerial economics, and silvicultural systems. Manuscripts regarding forest policy, forest economics, forest environmental education, landscape management, climate change mitigation and adaptation strategies, and drone applications for forest management are welcome. The Journal aims to provide a forum for international communication among forest researchers and forestry practitioners who are interested in the above-mentioned fields.

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