State-of-the-art Technologies of Forest Inventory and Monitoring in Taiwan

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Abstract.—Ground surveys, remote sensing (RS), global positioning systems (GPS), geographic information systems (GIS), and permanent sampling plots (PSP) were used to inventory and monitor forests in the development of an ecosystem management plan for the island of Taiwan. While the entire island has been surveyed, this study concentrates on the Hui-Sun and Hsin-Hua Experimental Stations of Chung Hsing University and the Northeast Coast National Scenic Area. The 7,500-ha Hui-Sun Experimental Station is located in the middle part of Taiwan, the 550-ha Hsin-Hua Forest Experimental Station is in the southern part of the island, and the 9,450-ha Northeast Coast National Scenic Area is in the northern part. GIS land-use maps derived from the aerial photographs of RS were used to select and survey PSP to obtain information about forest stand structure and growing stock. This information on the landscape patterns and changes of land use was used in the Hui-Sun Experiment Forest Station to detect changes in trends. The georeferenced surveyed data from the PSP were used to update forest attributes in GIS at different scales: landscape, forest stand, and tree. A tree location map was developed using compass, laser, and GPS techniques within each PSP. The georeferenced database allowed for the examination of the relationship between different species and their habitat. Research is ongoing. The problem of resource surveys and environmental monitoring at large scales and over the long term is also being studied.

Long-term forest management has two objectives: forest utilization and resource conservation. The problem most forest managers face is that of accessing the information to make necessary decisions. By integrating existing databases with well-designed forest inventories and monitoring systems, it is possible to focus attention on the indicators and criteria needed for forest ecosystem management planning and for forest policymaking. A forest inventory is one that obtains information about forest resources: the quality and quantity of the resources and the local land area characteristics (Husch *et al.* 1982). Forest monitoring involves evaluating the data collected in a forest inventory for estimating baseline conditions and for implementing management objectives (Haynes *et al.* 1996). The main focuses of ecosystem management (EM) are maintaining forest health, sustaining and restoring diversity, and restoring long-term productivity. Bioecological and social-economical criteria, however, also need to be considered. In Taiwan, there have been three forest inventories: in 1954, 1977, and 1994. The results of these inventories have been correlated with base maps, ground survey plots, aerial photos, and forest management records to produce land-use map digital terrain models (DTM) and area and volume of each working circle. These have all been linked in geographic information systems (GIS).

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Since it was developed in the 1960's, GIS technology has been widely used for ecosystem management (EM). GIS can be used to integrate map layers and attribute data derived from remote sensing (RS), data logging, computer mapping, database management, and geographic spatial analysis. This integration allows for the estimation of information and the evaluation of survey sampling design in various forest inventories and monitoring systems. The spatial statistical analysis capacities of GIS allow for site analyses, community analyses, planting species selection, density control, and land classification. The recent development of global positioning systems (GPS) and laser surveyors, has increased the ability to do forest ecosystem surveys and measurement integration. The more recent creation of permanent sampling plots (PSP) and adaptive management areas has been very important for conducting continuous forest inventories and for developing monitoring systems for EM. The data and information surveyed from these areas make it possible to compare natural and artificial aspects of management. In developing land information systems for EM and forest research, use of RS, GIS, GPS, and PSP is vital.

With the continued improvement and integration of remote sensing, GIS, and GPS technologies, their utility for forest inventories and EM monitoring systems will also increase. Remote sensing combined with PSP ground surveys will allow for updating existing databases and for monitoring the status, function, and change in the characteristics of a multiscale forest ecosystem. GIS makes this integration possible by improving accuracy in classification and estimation. It also provides effective cartographic control, and enables PSP to be located within the databases efficiently and accurately.

Ground surveys and RS (aerial photography, satellite imagery, etc.) are used to create and update an information database. Location is a very important factor in natural resource management and environmental monitoring, and GPS is a useful technology to determine the coordinates of a particular location. GIS is a versatile tool for storing, retrieving, processing, and analyzing the spatial distribution of significant properties of the earth's surface. PSP are created for the evaluation and adaptation of forest inventories and research, and for ground truth data collection.

The purpose of this paper is to demonstrate the use of state-of-the-art technology in the forest inventory and monitoring systems of Taiwan. Remote sensing, GIS, GPS, and PSP technologies are used in the development of sampling design, surveys, data management, and analysis of the forest inventory and forest monitoring system for EM in Taiwan. A flow chart of the forest inventory and monitoring system for EM in Taiwan is shown in figure 1.

STUDY AREA

Taiwan is a mountainous island of 3,598,000 ha off the southeast coast of Mainland China and north of the Philippines (fig. 2). The Central Mountain Range runs north-south down the center of the island and reaches elevations over 3,900 m. Three land-use surveys and forest inventories have been performed in Taiwan: from 1954 to 1956, 1972 to 1977, and 1989 to 1993. The Hui-Sun Experiment Forest Station is located in the

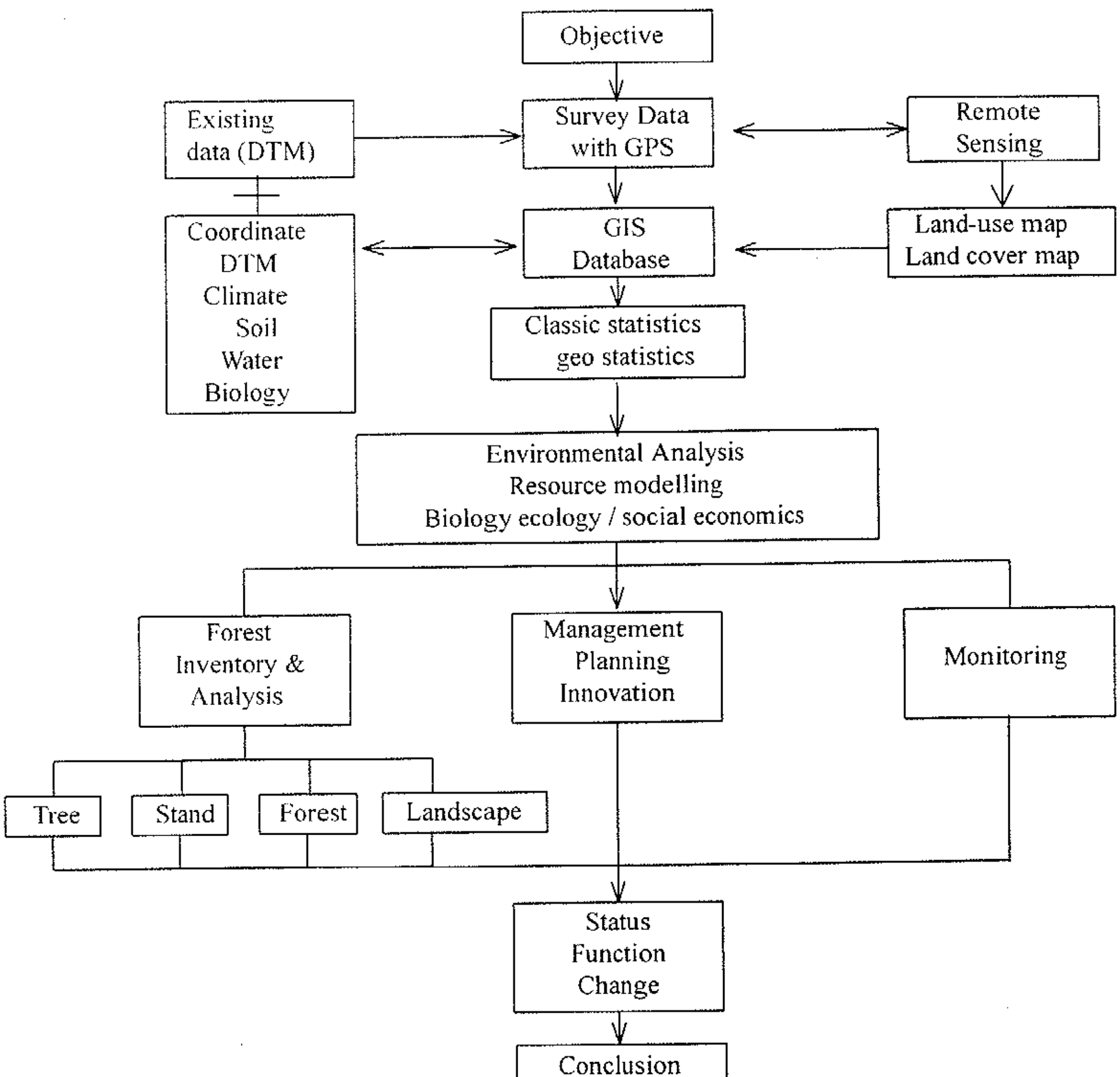

Figure 1.—*Integrating RS/GIS/GPS/PSP in forest inventory and monitoring.*

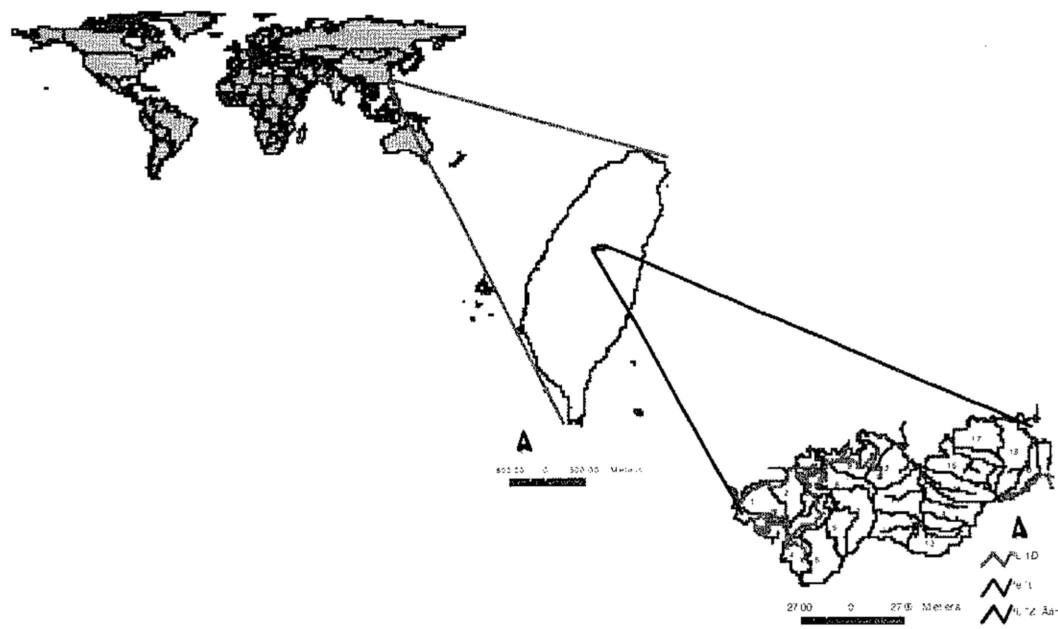

Figure 2.—*The location of compartments and rivers in Hui-Sun Experiment Forest Station.*

Beikangshi watershed in Nantou County in the central part of Taiwan (fig. 2). The station (7,600 ha) contains 19 forest compartments and 4 rivers. The elevation ranges from 550 m to 2,400 m. As a result of Taiwan's third forest inventory and land-use survey, there are several monitoring experiments in the station, including the Son-fen Mountain Area and a 400-ha Long-Term Ecological Research (LTER) site. This LTER site contains seed production gardens of *Schima superba* and *Calocedrus formosana*. Within the LTER site are many field studies of forest vegetation, biomass, productivity, parasitic plants, mammals, birds, insects, hydrochemicals, nutrient cycling, and meteorology. The Hsin-Hua Forest Station (fig. 3) is located in the southern part of Taiwan. It has 550 ha, of which 173 ha are privately owned, and it is made up of 10 forest compartments. The conservation of soil and water is the main function of this station. There are 62 permanent sampling plots set up within the station to monitor tree growth and yield. Fifty percent of the forest station is covered with a *Sweitania microphylla* plantation. The Northeast Coast National Scenic Area is located on the northeast coast of Taiwan: 9,450 ha of terrestrial area and 4,275 ha of sea area for a total of 13,725 ha. This is handled by the Taiwan Tourism Bureau.

MATERIALS

Digital Terrain Model

The Agricultural and Forestry Aerial Survey Team of the Taiwan Forestry Bureau made a DTM of Taiwan from control points and orthophoto models of Taiwan at the scale of 1:5,000 40 m x 40 m scale in 1981.

Temperature Data

The average temperature, tetratherm, maximum temperature and minimum temperature were derived from the long-term data sets of 26 meteorological stations distributed throughout Taiwan.

Precipitation Data

The average summer and autumn precipitation data were collected from 818 long-term stations, which include the 26 meteorological stations mentioned above.

Soil Data

The data on soil type, texture, and depth were determined from 3 km x 3 km systematical soil profile spots over 1,000 m in elevation. The spots had been surveyed in the third forest inventory and land-use survey of Taiwan.

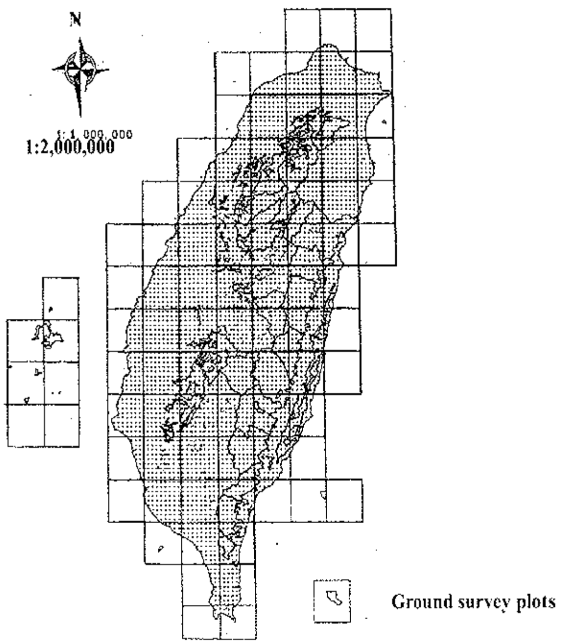

Figure 3.—*Location of Taiwan Forestry Bureau compartments and areas of private ownership within the Hsin-Hua Experimental Forest Station.*

Forest and Land-use Data

The entire island was surveyed using aerial photographs from 1987, old-base maps and aerial photographs, and ground survey plots systematically sampled in 1989-1993. The ground survey plots were selected from a 3-km x 3-km grid starting with the Chiang-Kai-Shek Memorial Hall in Taipei (Feng 1996). The resulting 4,002 ground survey plots are shown in figure 4. These plots were found to contain 66,979 individual trees (excluding supplemental plots containing 56,267 trees) (Feng 1996).

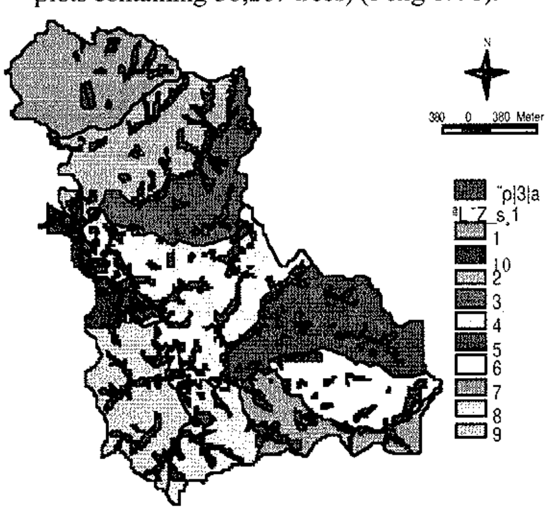

Figure 4.—*The location of the ground survey plots and working circles of the third forest inventory of Taiwan (1989-1993).*

METHODS

Data were collected from aerial photographs taken 1,200 ft above ground level and from ground survey plots (fig. 4). Spreadsheet and database management systems were used to input attribute data. A digitizer, scanner, and GIS software were used to input map data. Data were stored on rewritable 640 MB, 540 MB disks, CD disks, and 2 GB, 4GB, and 8 GM hard disks in formats suitable for use with Arc/Info and Arc/View. The SAS statistical package was used for analysis and development of mathematical models of the attribute data. Imagine was used for image processing. The functions of Arc/View used for spatial analysis were Overlay, IDW, Trend, Kriging, Spline of interpolation, spatial modules, and network modules.

RESULTS AND DISCUSSION

Multiscale and integration concepts were used in Taiwan's forest inventory and monitoring system. The scales used were island (Taiwan), region (working circles, Hui-Sun Experimental Station, Hsin-Hua Experimental Station, Northeast Coast National Scenic Area), landscape (land-use types, land cover), stand (Chinese cypress plantation, mahogany plantation, temperate natural community), plot, and individual tree. An environmental database was created to integrate the data of different areas of research.

Airborne Data Acquisition and Management System

The availability of frequent, relatively low-cost, and safe opportunities using sensors of different scales from a remote control aircraft platform to observe the earth's surface for environmental monitoring or other environmental experiments has become an essential component of today's remote sensing technique. A system like this not only provides valuable scientific data leading to new discoveries, it also allows for the acquisition of vital preliminary information for larger mission planning. A portable airborne data acquisition and management system (ADAMS) based on this concept is being developed in cooperation with the Department of Bioresource Engineering of Oregon State University. The goal is to integrate multiple remote sensors, spectral measurement devices, GIS, and GPS for automated airborne and field data acquisition and for near real-time data environmental analysis capability (Chen and Feng 1995). In the future, the expectation is for ADAMS to be used in remote control aircraft for forest inventory and monitoring at several low elevation scales.

Global Positioning Systems

GPS was developed to collect spatial data (coordinates and altitudes on the earth's surface) that can be put into GIS for storage and analysis. In a forest inventory, it is generally difficult to accurately position ground permanent plots from aerial photos. Ground surveys using differential GPS were made to determine the position of permanent plots in the Song-Fen Mountain Area of the Hui-Sun Experimental Station. GIS was then used to label the coordinate data. The results of this method showed that the coordinate data of base stations were congruous to the national standard of first class trilateration (Feng and Huang 1994). By using differential GPS, permanent plots, forest roads, and planting areas could be positioned accurately (Feng and Huang 1996). By putting the coordinate data into GIS, the spatial and attribute data of the permanent plots and areas of interest could be easily linked.

Sampling Design for PSP

The spatial analysis techniques of GIS are used to study the sampling allocation and sample-plot building of the Hsin-Hua Experiment Forest Station. In sample-plot building, buffer analyses of GIS were used to study the minimal sampling area with variance method, running mean method, diameter distribution method, and diversity method. Simulation was used to determine the numbers of unequal probabilities sampling with programming and GIS.

The Third Forest Inventory in Taiwan

For Taiwan's third forest inventory, remote sensing data of the entire island were used to detect changes over time from maps of land-use type, crown closure, and growing-stock classes. Combined with previous inventories, this inventory showed significant changes in forest area, increasing from 1,680,000 ha in 1977 to 2,100,000 ha in 1993. Currently, about 58 percent of Taiwan is covered with forest (Taiwan Forest Bureau 1994). The growing stock has been stable at about 170 m^3/ha.

This GIS analysis of Taiwan's economic forests was used to create a database for use in timber management. The database includes the position and physical condition of the forests, species composition, stand structure, stand development, and growing stock (Feng 1996). From this information, it is possible to develop a timber management strategy for Taiwan, and to consider several small scales as well as derive information at larger scales. In Taiwan, spatial and temporal factors of natural resources were used to integrate the survey data from different surveys and inventories of different scales.

A multiscale spatial database management system is being tested at the Guandashi Long Term Ecological Research (LTER) site in the Hwei-Sun Experimental Station (fig. 2). Current work focuses on aggregating and integrating the data of different spatial levels; developing a uniform input format for the database and DBMS; integrating the data from different surveys of different spatial scales; analyzing for information on status, function, and change; and sharing the data via the Internet and e-mail.

Spatial Interpolation

Maps of Taiwan summarizing the weather conditions (temperature and precipitation) were made by interpolating data from the meteorological stations (Kao and Feng 1998). Soil type and land use maps were made by interpreting the data collected from ground-survey plots in the third forest inventory (Taiwan Forest Bureau 1994). These data were also used to estimate average annual precipitation, temperature, and transpiration. Application of the Holdridge model of ecoregion classification to Taiwan resulted in categorizing Taiwan's habitats as belonging to the rainforest and moisture forest zones. This classification when combined with analysis of species composition within each zone will allow for the modeling of effects of climatic change within the island (Feng 1996).

Examples of Multiscale Analysis

In the Hui-Sun Experimental Station, aerial photographs and data from Taiwan's first, second, and third forest inventories (Feng and Huang 1996) were combined to produce topographical land-use maps. In addition, a detailed study on the growth rates of China fir (*Cunninghamnia lanceolata*) in plantations with various thinning treatments was also made (Feng 1997). The results of these analyses showed that the type and diversity of forest stands have changed over the past 30 years with a trend towards increasing complexity and diversity as native broadleaf species invade the plantations of China fir. Furthermore, the thinning experiments demonstrated that China fir grows most efficiently at very high thinning rates. Thinning rates of 60 percent, however, leave light gaps in the stand that may encourage invasions by native broadleaf species. Current work is studying the invasion rates by broadleaf species and the effect of different-size light gaps.

In the Northeast Coastal National Scenic Area, a similar study was conducted (Feng and Huang 1997a). In this area, land use over the past 30 years has also changed, but not because of natural invasions by native species. In this case, the change has come from increased human activity: building and the creation of plantations. As this trend has been identified, current studies are examining the effect these changes may have on the area.

In the Shin-Hwa Experimental Station, studies have focused on evaluating tree growth rate, growing-stock volume, and structure in stands of *Swietenia macrophylla*. Studies such as this and the China fir study in the Hui-Sun Experimental Station are necessary. These studies collect information on growing stock and volume, on forest cover, on changes in land use over time, and on changes in biomass from year to year that will be useful in evaluating carbon sequestration and emission in Taiwan's forests. Studies of this sort are of increasing importance as high levels of carbon in the atmosphere are being identified as a cause of global warming (Chen *et al.* 1997).

An Example of Integration

In the Northeast Coast National Scenic Area, GIS is being used to integrate vegetation data from permanent plots and a moth-trap inventory of local insects. From 9 months' trapping in 1995, a total of 1,790 individuals representing 19 families and 144 species of insects were collected. This study identified the summer months as the most active season for insects, and it identified the most common species in the area (Feng *et al.* 1998a, b). Current work is focusing on collecting the microhabitat data and correlating this with environmental trends and the observed insect diversity and frequency. The goal is to gain enough understanding of the system to provide some focus for long-term monitoring. There is also a strong interest in correlating each species with a host plant.

In the Hui-Sun Experimental Station, many different research projects are being done at the Guandashi LTER site (Feng 1997). From the GIS analysis described above involving scales at the levels from station land-use categories to individual tree growth rates, the conclusion was that collecting data at the level of the individual tree had the most utility. Currently, all the data collection for the different research projects at the LTER site is encouraged to be at the level of individual trees (Feng *et al.* 1998a). If this is successfully managed, then the data from studies of amphibians, parasitic plants, small mammals, and habitat can be integrated into GIS for a more comprehensive picture of the forces at work at this LTER site.

Forest Ecosystem Management

Studies such as the ones outlined here that inventory and analyze the forests of Taiwan are needed for forest management. These studies have concentrated on the forest stand types and the natural and human activities that occur within each stand. In the Hsin-Hua Experimental Station, analysis has also included maps of water systems, transportation systems, and land ownership and administration (Feng and Tsai 1998). Combining forest inventory data with maps of human activity within and around the forest is necessary to better model the changes that are occurring.

Forest ecosystem management (EM) must begin by considering the never-ending demand of human beings for goods and service and the limits of biological and ecological resources. With the limited knowledge and techniques currently available, the problem is determining how to manage a forest. To resolve this problem, it is necessary to integrate the knowledge, interests, and demands of the public, scientists, and forest managers. Before integration can be done, however, criteria for sustainable management at different landscape scales must first be created. Once the criteria have been decided upon, data can be collected from ground survey of permanent plots, remote sensing, photogrammetry, GPS, and social surveys for integration into GIS for spatial, non-spatial, and temporal analysis. In Taiwan, "managerial experiments" have been designed using biological, ecological, sociological, and economical knowledge and techniques to develop an adaptive management system. Models of different forest scenarios have been used to plan ideal forests for the future. To develop these "managerial experiments" and forest scenario models, the criteria and index of EM monitoring had to be measured and evaluated first. With the results of EM monitoring, it is possible to develop and improve the practice and procedure of forest ecosystem management in Taiwan.

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