Flood Inundation and Rice Crop Damage Analyzed by Multitemporal TM Data

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Abstract

The paddy rice damage caused by a flood in Japan has been assessed using multitemporal TM images. We defined Water Turbidity Index(WTI) and Perpendicular Vegetation Index(PVI) to measure the flood water turbidity and rice crop yield, respectively. PVI was correlated to measured rice damage and the water turbidity of the flood water was correlated with the rice yield decrease. The flood rice damage could be estimated not only from the image acquired before the harvest but also from the image immediately after the flood.

1. Introduction

A powerful typhoon struck the Kanto district of Japan on August 4 and 5, 1986. Precipitation in excess of 400 mm was recorded in several areas and floods occurred. The rice crop was at boot stage (10-20 days before heading date). The resulting damage to paddy rice exceeded 20 billion yen. In such agricultural emergencies, several agricultural agencies need to assess the damage (decrease in yield) immediately. At present, the extent of the damage in a region is estimated from a very small number of damaged fields for which yield is determined by direct sampling. However, the damage cannot be estimated accurately because the sample is limited.

Landsat and other satellites have the capability to document conditions in many individual paddies and to provide a thematic overview. Several workers have estimated crop biomass and yield using satellite data (Barnett and Thompson 1982, Wiegand and Richardson 1979, 1984). On the other hand, vegetation indices derived from field measurements of reflectance factor relate closely to LAI, phytomass, and yield of many kind of crops (Jackson et al. 1983, Jackson 1983, Gallo et al. 1985, Wiegand and Richardson 1987). However, the indices derived for ground observed reflectance factors cannot be applied directly to satellite data without taking sensor and satellite calibration into account (Price 1987).

We were fortunate to acquire Landsat thematic mapper (TM) scenes one day after the typhoon abated that recorded the inundated paddy fields, and scenes of the same sites again one month after the inundation that documented the damage. We converted these data into reflectance factors using coefficients provided by Price (1987) and defined a turbid water line (TWL) and water turbidity (WTI) and perpendicular vegetation indices (PVI) (Richardson and Wiegand, 1977) based on it for inundation-damaged paddy rice. TM bands 3 (630-690nm:RED) and 4 (760-900nm:NEAR-INFRARED or NIR) were used. Our objective was to relate flood water turbidity to resulting damage in terms of rice yield using these indices at two test sites, and to discuss how such a relation can be used in rice crop damage estimation.

2. Study area and image data

We analyzed two test sites (Figure 1) in northern Kanto district in Japan, where paddies were inundated during a typhoon that heavily damaged the rice crop. Both test sites included inundated paddies along a river near the area where the river reaches a lake.

Figure 2 displays TM band 3 images showing the inundated paddy fields in the Hinuma (a) and Ishioka (b) areas on August 6, 1986, immediately after the typhoon abated. In these images the more turbid the flood water, the brighter the images appear. When this image was acquired, the rice crop was the boot stage of development (approximately 10 days prior to heading); the inundation continued for 1 to 5 days.

Figures 3(a) and (b) display the TM band 4 (near-infrared) images, corresponding to those in Figure 2, obtained on September 7, 1986, one month after the inundation. In these images, healthy rice appears bright and damaged rice appears dark. Heavily damaged rice was dead and abandoned (not harvested). When this scene was acquired, the rice crop was in the middle of the grain filling stage.

3. Method

In order to examine the correspondence between the inundation and the damage, the TM scenes for August 6 and September 7 were overlaid. TM bands 3 (630-690nm) and 4 (760-900nm) were selected for our analyses, because agronomically important parameters, such as leaf area index (LAI), are known to be sensed by these red and near-infrared bands (Wiegand et al. 1979). Two test sites were selected (Hinuma and Ishioka) that were 250 x 200 and 250 x 160 pixels in size respectively. The two channel data for each test site formed 4 channel multitemporal, multispectral data set for each site.

To extract the pixels for the paddy fields, a supervised classification was carried out using these multitemporal image data. Within the rice paddy pixels, there were several distinguishable spectral categories that ranged from undamaged (category A) to abandoned (category G) that could not be distinguished without using the multitemporal features. After this classification of damage categories, we subsampled paddy pixels taking every fifth pixel on every fifth line to reduce the data volume for statistical analyses. Image analyses were carried out using the NIAES Remote Sensing Laboratory's analyzing system, consisting of 4Mbyte CPU, 500Mbyte disk, and 8 image planes with 256 gray levels. Representative pixels from the rice categories such as inundated or not inundated in Hinuma scene are identified by letter in Figures 4 and 6.

Actual rice yield was determined at seven test sites in Hinuma area. The yields of 3 to 5 (3.5m) in different paddies at each sample site were measured on 25 September. The average yield for each test site was used as the ground truth, while the TM reflectance factors for each test site were determined from the corresponding 3x3 pixels averaged for those same sites.

TM digital counts observed at the top of the atmosphere are affected by the atmosphere, sun elevation, sensor degradation, etc. Therefore, a spectral index developed using a given scene cannot be directly applied to another scene nor to other sensor systems without calibration to reflectance factors. We used the calibration method and coefficients summarized by Price (1987) to convert Landsat-5 TM digital counts into spectral albedos, defined as the spectral radiance observed divided by the equivalent solar radiance calculated for each channel. They are comparable to spectral reflectance factors measured on the ground for the same wavelengths. Hereafter in this paper, we call them spectral reflectance.

4. Results and discussion

(1) Scatter diagram of red near-infrared band

Figure 4 displays the scatter in red and near-infrared reflectance space of inundated paddy pixels in the test area on August 6, 1986, one day after the typhoon ended. Sample pixels were identified with letters as follows:, A,B,C - Not inundated, but paddy water depth increases form A to C; D - Canopy partially inundated with clear water; and, E,F,G -paddy inundated with increasingly turbid water, respectively.

(2) Turbid water line

As is the case of soil line (Richardson and Wiegand 1977), turbid water pixels fell on a line. Using the 12 water pixels of variable turbidity (sediment load), we determined the equation of the turbid water line (TWL) by regression analysis. The equation is given in Figure 5. Almost all water pixels are close to this TWL line, which goes through the origin. We needed to use this TWL instead of soil line because paddy rice grows out of turbid water rather than soil. We used this line as a base to define PVI, and the water turbidity index.

(3) Water turbidity index and perpendicular vegetation index

The linear relation between water turbidity and satellite spectral radiance in the red band has been reported (Khorram 1981, Lathrop and Lilesand 1986). We defined water turbidity index (WTI) as the distance from the origin along the TWL to measure the turbidity (sediment load) of flood water. This WTI expressed in terms of spectral reflectance should hold worldwide, if properly placed in TM 3 and 4 band space.

Richardson and Wiegand 1977 developed the perpendicular vegetation index (PVI) in order to extract information about vegetation independent of the soil background. Here PVI is the distance from the TWL. The interrelation among WTI, PVI to TWL are given in Figure 5 along with their equations. Since the turbid water line passes through the origin, the coefficients in the WTI (or brightness) and PVI (or greenness) equations are the same as yielded by the n-space procedure of Jackson (1983).

Figures 6 (a) and(b) relate WTI and PVI of paddies in the Hinuma (a) and Ishioka (b) areas on August 6, the day after the typhoon abated. The turbid water line determined for the Hinuma site was applied to the Ishioka test site. The turbid water pixels in the Ishioka area were also on the TWL calculated from the Hinuma data. The soil line has been found to apply globally, so that the analogous turbid water line for grayish and brownishi soils in the Hinuma data should be applicable elsewhere.

(4) PVI and rice yield

We applied the PVI equation based on the turbid water line for the August 6 scene to TM data acquired on September 7, 1986, one month later, to see how much the paddy rice was damaged. Many investigators have related vegetation indices calculated from spectral reflectance in visible and near-infrared bands to biomass, LAI, and yield (Patel et al. 1985, Aase and Siddoway 1981, Jackson et al. 1983, Wiegand et al. 1979, Wiegand and Richardson 1984, Barnett and Thompson, 1982, Gallo et al. 1985, Asrar et al. 1985, Hatfield et al. 1985). We also related the PVI observations to yield.

Figure 7 relates measured yield and PVI for paddies ground truthed in the TM scene. Using this regression equation given in the figure, we could estimate the regional damage. The yields ranged from zero for abandoned (not harvested) paddies to almost 5 t/ha for paddies that were not damaged. The regression equation is given in the figure.

(5) PVI on August 6 and PVI on September 7

Figure 8 shows the PVI change from August to September of paddies in the Hinuma area, that were not inundated. Rice canopies corresponding to the letters A, B, and C were not inundated, but paddy water depth increased form A to C.

Compared with the 1:1 line given in the figure, it is apparent that the normal paddies (not inundated) did not change in PVI, but paddies with deeper background water (category C) had lower PVI on August 6 and recovered to an average PVI -25 by September, where the normal paddies (Category A) had an average value of about 30 in both August and September. The paddies that had a PVI of 25 in September instead 30 or more experience a slight decrease in yield.

(6) WTI on August 6 and PVI on September 7

Through the yield estimation, we noticed that the yield decrease of inundated rice could be related to the turbidity of the flood water. Because damage to the rice plant was at least partially due to the sticking of mud to the leaves and stems, it is reasonable that the more turbid the flood water, the heavier the damage. We could monitor the flood water turbidity by WTI on August 6 and the yield by PVI on September 7. Figure 9 shows this relation between WTI and PVI in the Hinuma (a) and Ishioka (b) areas with regression line. For the Hinuma area, PVI (yield) in September was constant until the turbidity (WTI) in August exceeded 9, beyond which the PVI decreased linearly as WTI increased. In contrast, data for the Ishioka area indicates a linear decrease in PVI in September until the turbidity (WTI) reached 9 to 10, beyond which the relation may have split into two paths. A plausible explanation of the two paths is as follows: The slope would be less for those paddies that were inundated for only a short time and greater where the muddy water stayed longer and caused rotting of leaf and other tissue (i.e. increased damage). However, we lack direct observations to substantiate these conjectures.

5. Conclusion

TM images of paddies acquired August 6, 1986, (immediately after the typhoon of August 4 and 5) and again September 7, (three weeks before harvest) were used to relate inundation damage to rice yields. That was accomplished by using the turbid or sediment laden water pixels, to determine a turbid water line. The brightness or water turbidity index (WTI) along the turbid water line and the perpendicular vegetation index (PVI) for paddy rice were defined using this line. Rice yield data measured for undamaged and damaged paddies were pooled and related to the PVI calculated from the respective TM reflectance. The yield could estimated from the PVI using the regression equation. The relation between flood water turbidity at boot stage could be monitored using WTI and the damage to yield could be measured by PVI. This result shows the possibility of an early assessment of the crop damage to rice by flooding by run-off waters of monsoon, typhoon, or hurricane associated rainfall. The relation between flood water turbidity and rice damage is less clear than between PVI change and yield, and probably depends on the growth stage at the time of flooding, water temperature, duration of flooding, and other factors including the geography and characteristics of the run-off areas. However, the use of satellite data to assess crop damage in terms of spectral reflectance changes of the canopies during the reproductive stage is well developed and has a sound basis (Wiegand 1984, Wiegand and Richardson 1984, 1987).

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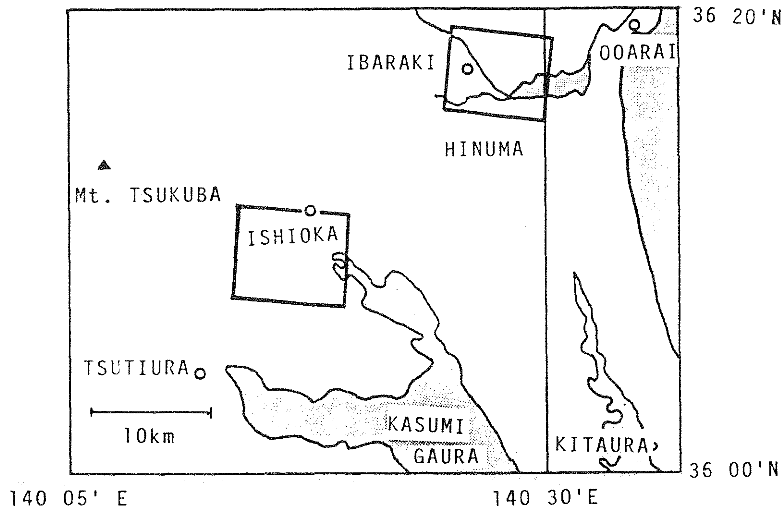


FIGURE 1 Test sites location map.

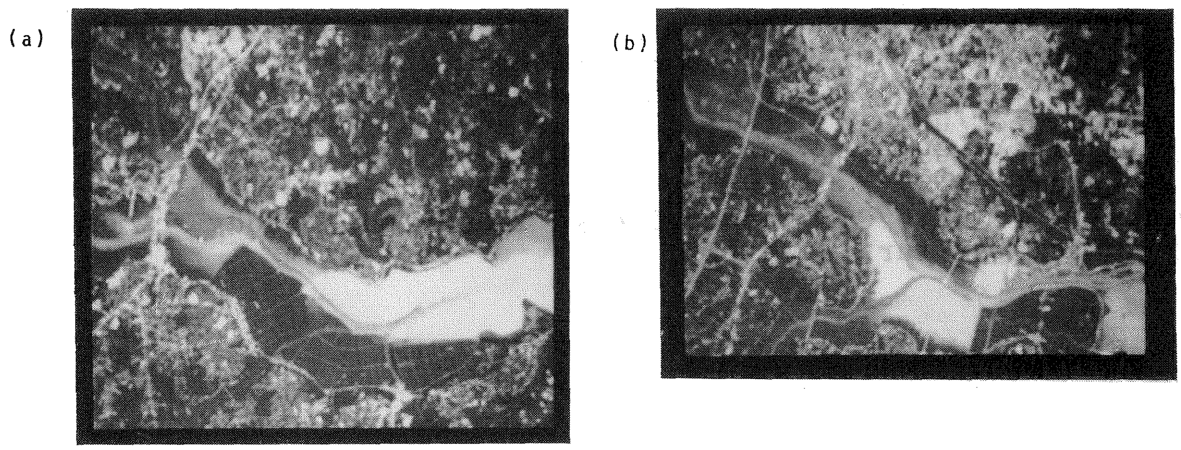


FIGURE 2 (a), (b) TM image (band 3) on August 6, 1986, showing inundated paddies and surroundings at Hinuma (a) and Ishioka (b) test sites.

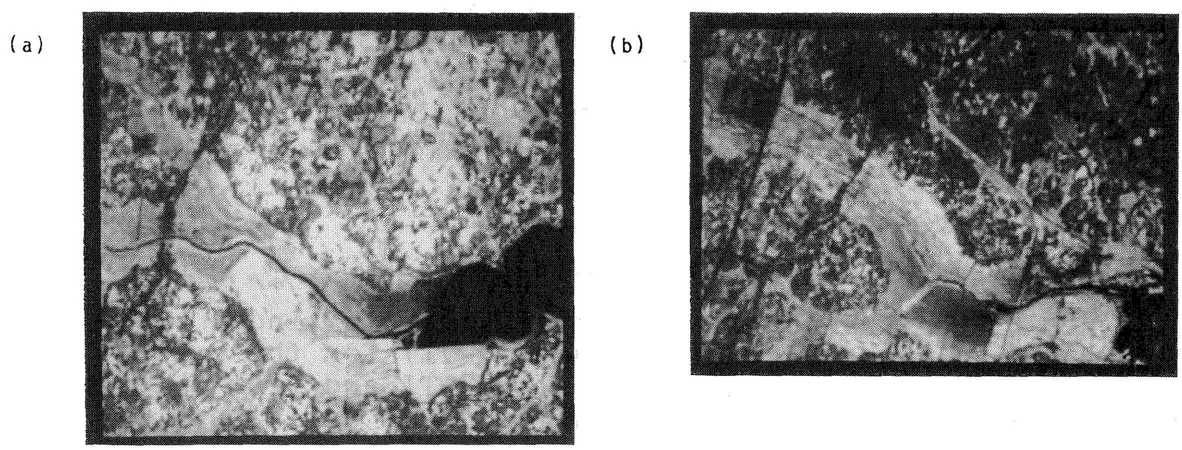


FIGURE 3 (a), (b) TM image (band 4) on September 7, 1986, showing damaged paddies and surroundings at Hinuma (a) and Ishioka (b) test sites.

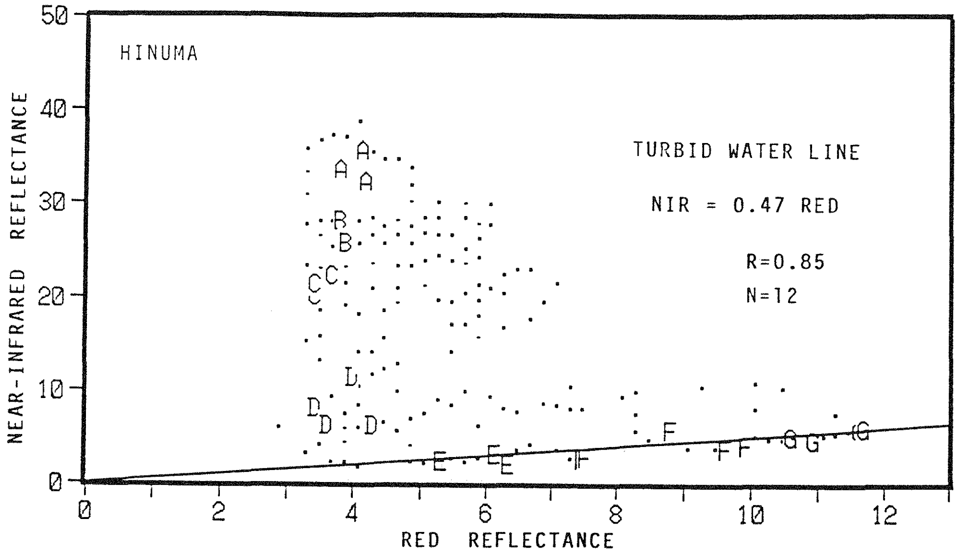


FIGURE 4 Scatter diagram of red band (TM3) and near-infrared band (TM4) of paddy field pixels in Hinuma on August 6, 1986. The turbid water line (TWL) was determined using categories E,F and G. Where, sample pixels of each category were selected as, A,B,C: not inundated paddy / D: canopy partially inundated with clear water / E,F,G: respectively inundated paddy with increasingly turbid water.

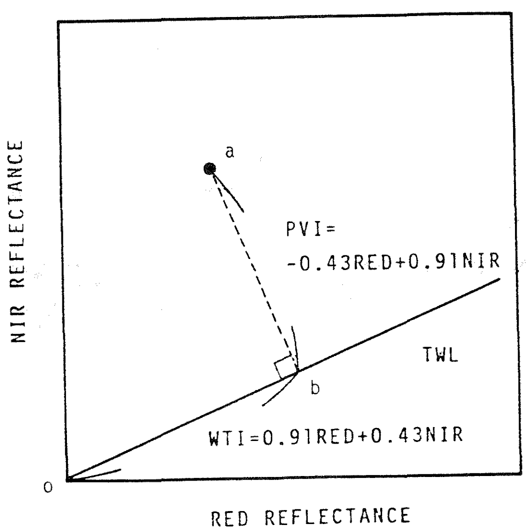


FIGURE 5 Illustration of the water turbidity index (WTI) and perpendicular vegetation index (PVI) for these data. Distance from o (origin) to b is the WTI and from b to a is PVI. Defining equations for WTI and PVI are given.

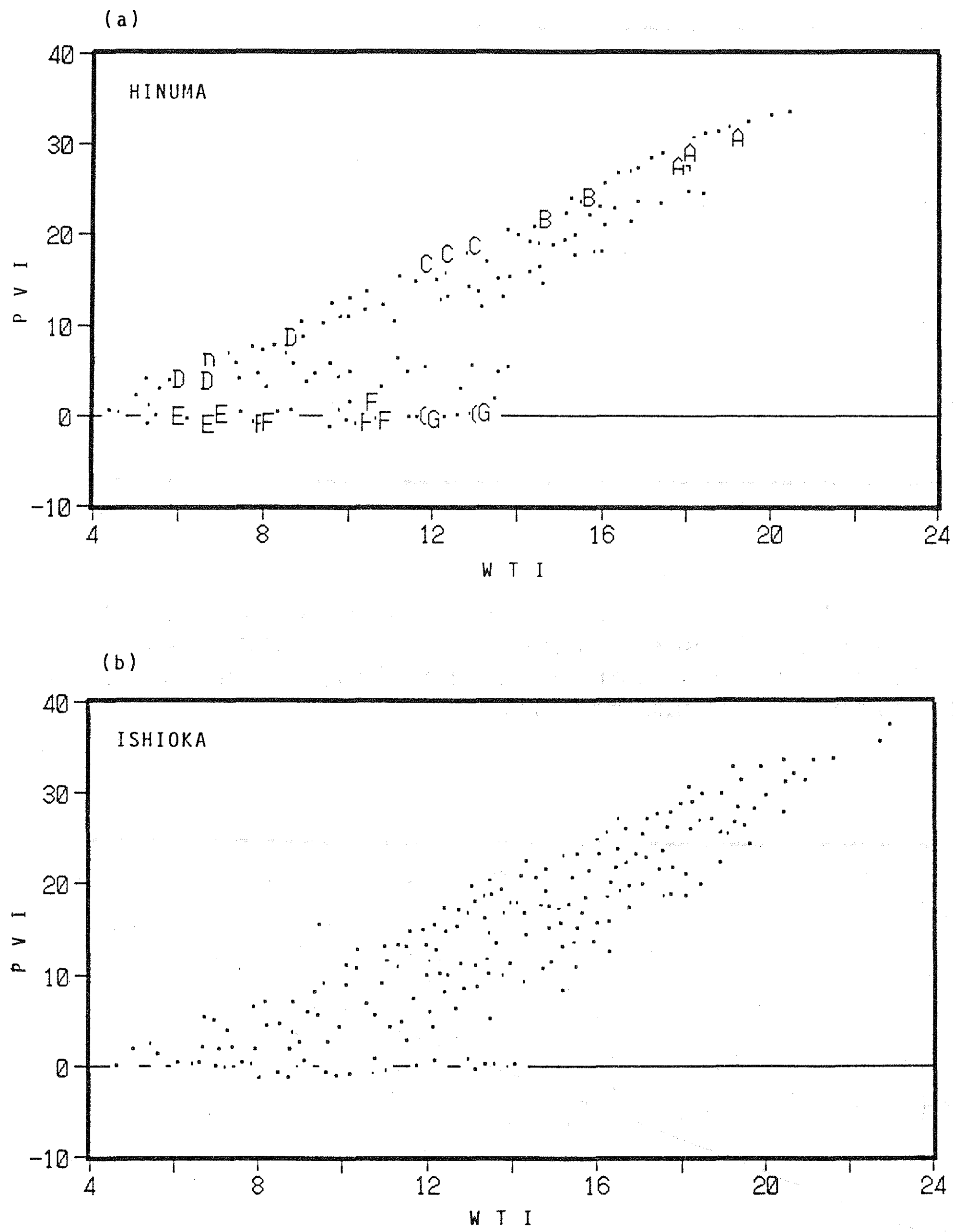


FIGURE 6 (a), (b) Water turbidity index (WTI) versus perpendicular vegetation index PVI for August 6, 1986, TM scene at two test sites, Hinuma (a) and Ishioka (b). The turbid water line determined for Hinuma site was applied to Ishioka test site. A,B,C: not inundated paddy; D: canopy partially inundated with clear water; E,F,G: inundated paddy with increasingly turbid water, respectively.

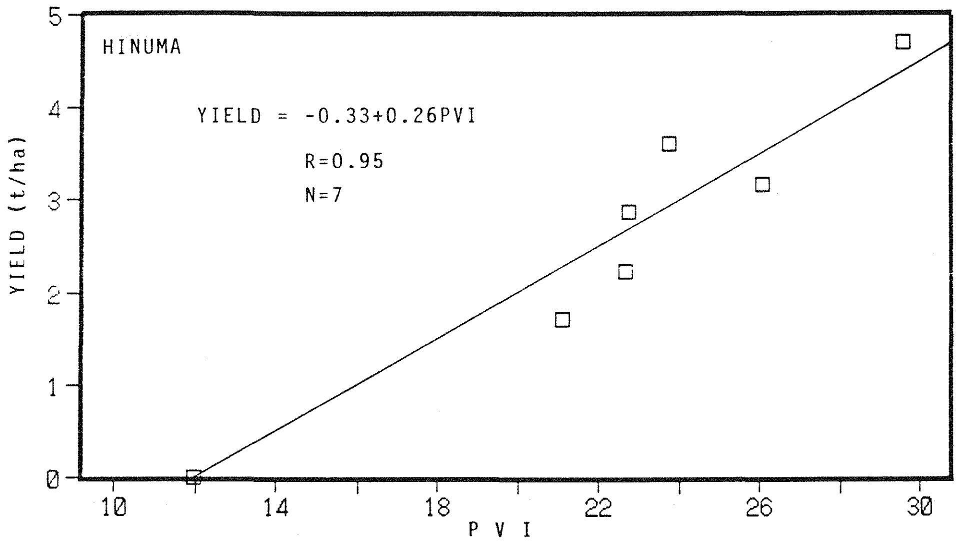


FIGURE 7 Yield of brown rice versus PVI for 7 TM data sample sites. TM scene (September 7, 1986) site yield ranged from zero for abandoned (not harvested) paddies to almost 5t/ha for undamaged site.

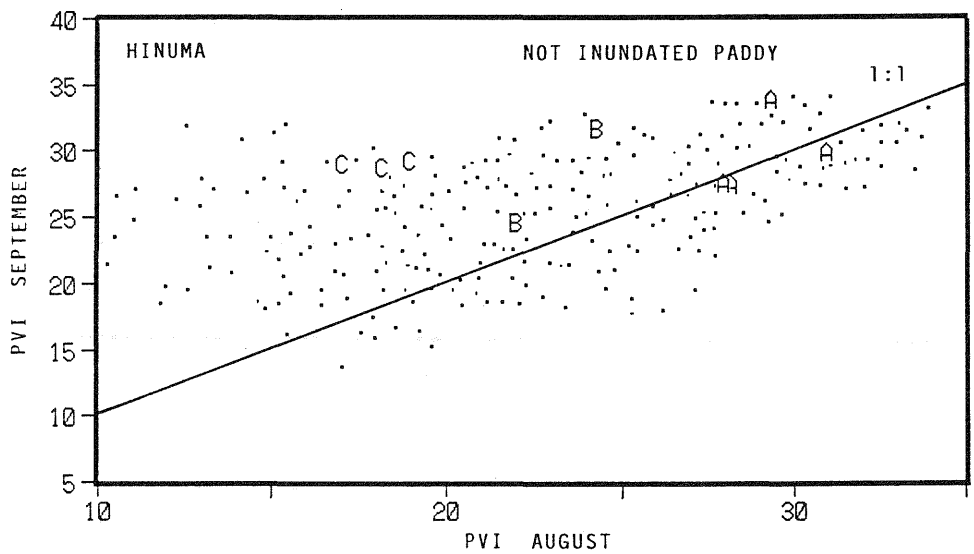
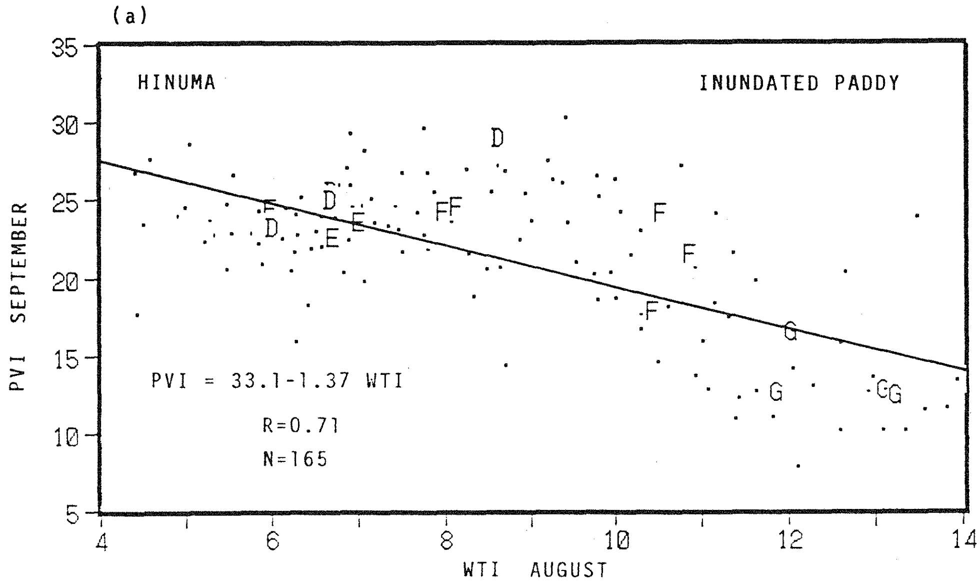


FIGURE 8 PVI (September 7) versus PVI (August 6) of paddies not inundated (most of the canopy was above water) in Hinuma area.



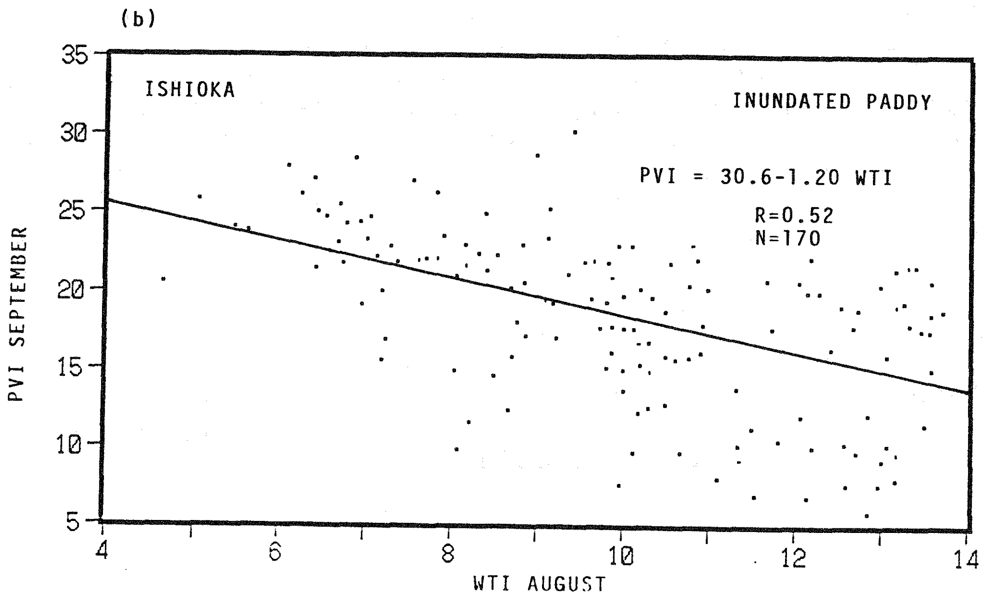


FIGURE 9 (a),(b) PVI (September 7) versus WTI (August 6) for paddies inundated with clear or turbid water in Hinuma area (a) and Ishioka area (b). Regression line for each test sites were given. This relation shows that the more turbid the water was, heavier damage was brought to the inundated paddy rice. However this relation is not linear nor clearly determined. D: canopy partially inundated with clear water / E,F,G: respectively inundated paddy with increasingly turbid water.