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Investigation of Fires in Natural Ecosystems of the Ukrainian Roztochchiya by Wildland Fire Dynamics Simulator Model

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ABSTRACT

Fires in natural ecosystems require a comprehensive approach due to the dependence of these processes on many factors – climatic conditions, moisture content of combustible material, type of ignition source, soil temperature regime, availability of possibilities and tools for extinguishing, presence of fire-fighting obstacles, organization of localization and elimination. The investigation of natural fires today takes into account (developed and effectively used) computer models, which are based on numerical methods of the physics of combustion of substances and materials. In the presented work, a study of the fire at the site was carried out, which included the growth of grass and other components of the phytocenosis, particularly shrubs. The research was carried out taking into account the environmental conditions and the combustible material's physical and chemical properties. In general, the fire simulation lasted 180 seconds. Rapid burning stopped 66 s from the beginning of ignition, and after that, single burning and smoldering of the studied area were observed. It was established that the maximum flame temperature was more than 1250 °C, which was observed in 33 s within the limits of burning grass in stacks. The maximum power from the fire of the studied area is reached approximately at the 65th second and was 209650 kW/m^3, and starting from the 66th second, it was decreasing. It should be noted that the species composition of the pyrogenic succession is depleted, and on the site of the fire, there is a scattering of plants and a spontaneous arrangement in the studied area. The predominance of *Asteraceae* in the pyrogenic succession is a rather positive phenomenon because they are the most widespread family of the flora of Ukraine and have great practical applications and are used as medicinal, food, fodder, honey, oil, and decorative species.

Keywords: fire, ecosystem, modeling, WFDS, pyrogenic succession.

INTRODUCTION

Modeling of the processes of occurrence and spread of fires, especially in natural ecosystems, is gaining more and more development. Prospects for the application of empirical, physical, and mathematical models in combination with computing technology provided the possibility of computer models implementing that not only create an idea of the combustion process but also give the opportunity to observe its progress. For natural fire research, computer models have been developed and are effectively used today, based on numerical methods of the physics of combustion of substances and materials. An example of this is the use of the WFDS model (User Guide to WFDS…, 2022), which is intended for the study of fires in natural ecosystems, namely forests (bottom, upland) and grass. The basic structure of the model assists in the investigation of the features of flame propagation through a combustible surface, the estimation of the combustion parameters, and the establishment of the fire hazard indicators of the combustible environment. At the same time, it is also important to study the processes of combustion of natural combustible material depending on changes in the physical and chemical properties of this material, the type of ignition source, and hydrometeorological conditions.

In the global context, numerous studies are carried out on the modeling of fires in natural ecosystems. Researchers (Mansoor et al., 2022) have proved that drought affects the moisture content of fuel, causing physiological changes in forest vegetation, which leads to forest fires. The stability of forests deteriorates due to temperature and drought stress during the development stage of the plant life cycle, which leads to a change in plant species in these areas. Forest fire occurrences can be managed through appropriate management strategies such as sustainable, community, and urban forest management. Careful monitoring of stressors, utilization of forests for personal needs, environmental education, and planting of native and new indigenous plant species are tools that can help in effective forest management.

The paper (Valero et al., 2021) gives the application results of multi-accuracy approaches to the problems of forecasting the spread of fires in nature. The proposed methodology can also be used to analyze the uncertainty in other relevant parameters of fire behavior, such as heat transfer parameters, fuel consumption, and smoke generation.

The scientific paper (Ronchi et al., 2019) presents a WUI multiphysics framework for forest fire evacuation simulation, including three main simulation levels: forest fire, pedestrians, and road traffic. Currently, these layers are mostly modeled in isolation, and there is no comprehensive model explaining their integration. The key characteristics required for system integration are identified, namely: a consistent level of improvement of each level (i.e., spatial and time scales) and their application (e.g., evacuation planning or emergency response), as well as full data sharing.

The study (Castillo Soto et al., 2022) proposed a method for determining the optimal safe distance or vegetation-free strip, mainly in WUI priority areas. These priority areas have been identified and reviewed taking into account historical risk, potential risk, potential fire behavior, and difficulty of resistance to control or suppression. The calculation of the safe distance was based on a physical model of radiation heat transfer according to the potential fire behavior of each zone. Recommended vegetation-free strips ranged from 5 m to 32 m for buildings due to surrounding fuel patterns and terrain slopes. These recommendations differed from the standard values used in operation regardless of the fuel model. The maximum recommended safe distance ranged from 23 m (territory of Chile) to 32 m (territory of Spain) (Castillo Soto et al., 2022).

A number of works are devoted to the study of fires using WFDS. In paper (Drach et al., 2022) the peculiarities of the change in the fire front propagation rate depending on the height of the grass were studied using such a model. In paper (Meerpoel-Pietri et al., 2022), the loss of mass and the power of heat release from the combustion of chopped wood were investigated. Also, there are the works of foreign scientists that are worthy of attention, in particular those aimed at researching the fire hazard of coniferous plantations. But we note that the processes of the occurrence and spread of fires in grasses and shrubs have not been studied enough. Therefore, a study of the fire at the site was carried out, which included the growth of grass and other components of the phytocenosis, particularly shrubs.

The dynamics of shrubs burning was numerically investigated (Morandini et al., 2019) using WFDS. A bulk density model was developed from the characterization study and used as input to the numerical code. The predicted HRR corresponds to the experiments, although the simulation results need improvement in the initial phase of combustion.

In our scientific works, we have already presented the results of research of fires in natural ecosystems within the boundaries of the Ukrainian Roztochchiya. Namely, these fire's distribution and the concentration of their occurrence were carried out using Voronoi diagrams (Popovych et al., 2019). The effect of high soil temperatures on the migration of heavy metals was established in (Popovych et al., 2021).

MATERIALS AND METHODS

The research was carried out taking into account the environmental conditions and the combustible material's physical and chemical properties. The meteorological conditions for the research were as follows: air temperature +27 °C, relative air humidity 24.5%, variable wind direction 1.5 m/s, atmospheric pressure 746 mm Hg, the moisture content of combustible material: grass in the uncut state is 13.11±1%, and grass cells in the form of stacks – 35.15±1%. Other physical properties of the combustible material were used in accordance with (User Guide to WFDS…, 2022). For simulation, a rectangular area with dimensions of 20×16×6 m was built. Arson was carried out by forming a 3×0.3 m combustible strip at the beginning of the experimental area. The simulation time was 180 s. For monitoring the modeling process, the Smokeview application was used, which is designed to visualize numerical calculations generated by fire models. This application visualizes flames, smoke, and other parameters of a fire using conventional scientific methods, including the display of tracer particle flow (2d or 3d contours of gas flows), using data such as temperature and flow vectors showing its direction and magnitude. Smokeview also visualizes static data at a given time using 2D or 3D contour data using temperature and flow vectors with their direction and value taken into account.

The species composition of the pyrogenic succession was established using the determinant (Kucheryavy, 2003). The abundance of species of pyrogenic succession is described according to two scales – Drude and Braun-Blanquet (Honcharenko et al., 2003). The model flame was created in the natural conditions of the Ukrainian Roztochchiya (Fig. 1).

RESULTS AND DISCUSSION

For the objectivity of the experiment, the change in fire hazard indicators was studied, in particular, the power of heat generation and temperature according to the burning time. For this purpose, in the simulation file, virtual thermocouples were arranged in 3 rows along the length of the experimental area, the interval between the rows was 4 m. Using the Smokeview application, an image of the combustion process was obtained in the 1st and 2nd minutes from the start of ignition of the combustible material, as well as dynamics of radiation power during a fire (Fig. 2).

In general, the fire simulation lasted 180 seconds. Rapid flaming burning stopped 66 s from the start of ignition, and after that, single burning and smoldering of the studied area were observed. The investigated power of fire heat release according to the simulation result is shown in Fig. 3.

It was established that the maximum power from the fire on the studied area was reached approximately at the 65th second and was 209650 kW/m^3, and starting from 66s, this value had a tendency to decrease.

The maximum flame temperature was more than 1250 °C, which was observed after 33 s within the limits of burning grass in the form of stacks. However, from the 66th s, a decrease in the flame temperature in the combustion environment of the experimental area to the ambient temperature was observed (Fig. 4).

According to Kucheryavyi (2003), pyrogenic successions are caused by fires in forests, steppes, swamps, etc. The growth of 12 species, which were assigned to 10 genera (Table 1), was observed on the experimental site over the next three years.

It should be noted that the species composition of the pyrogenic succession is depleted, and on the site of the fire, there is a scattering of plants and a spontaneous arrangement. The abundance

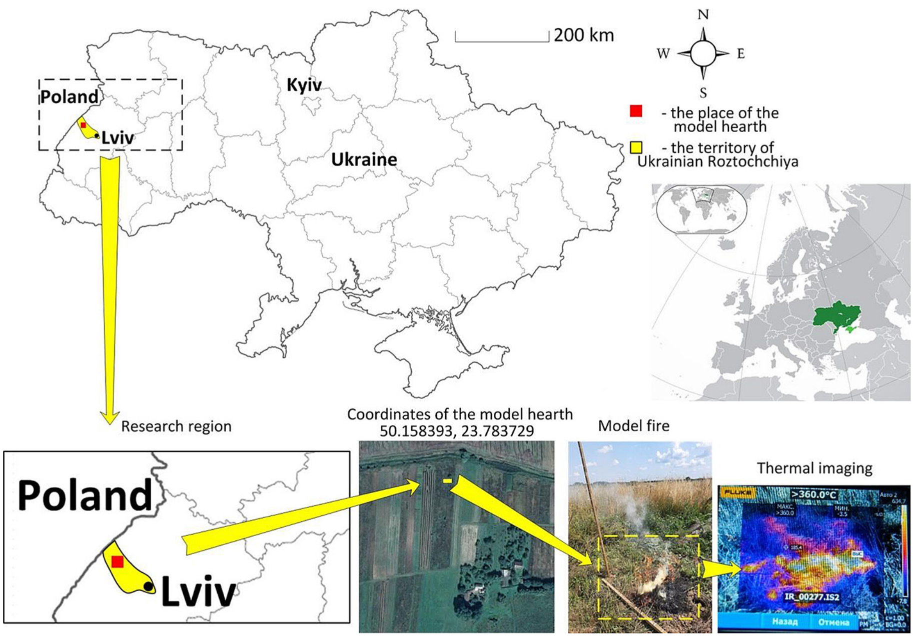

Figure 1. Location of the experimental site

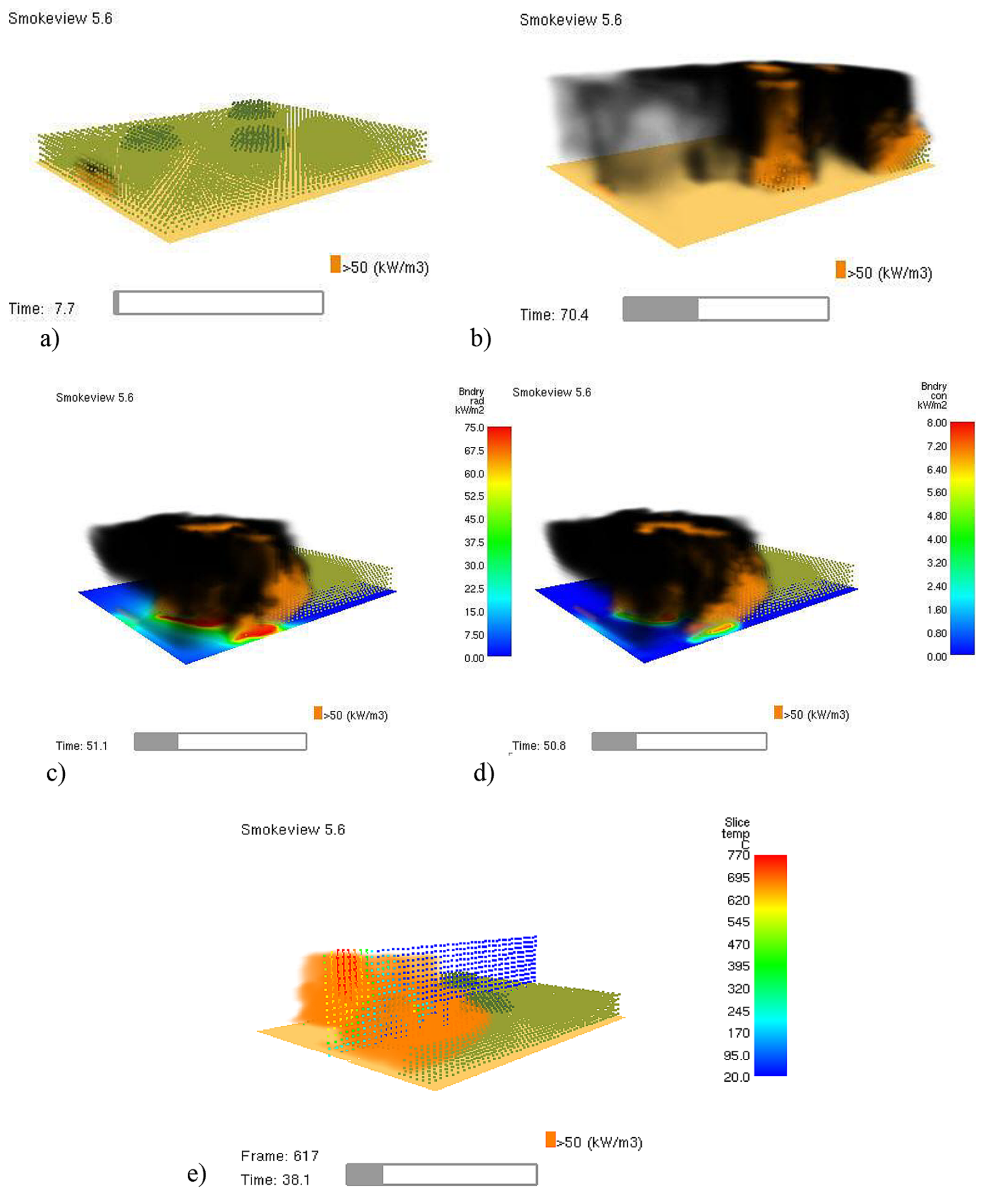

Figure 2. Visualization of the fire process: (a) at the 8th second from the start of burning, (b) on the 71st second from the start of burning, (c) with a reflection of the radiation power in the fire environment, (d) with a display of the power of the convective flows in the fire environment, (e) with a display of the value of the distribution of the flame average temperature in the fire environment

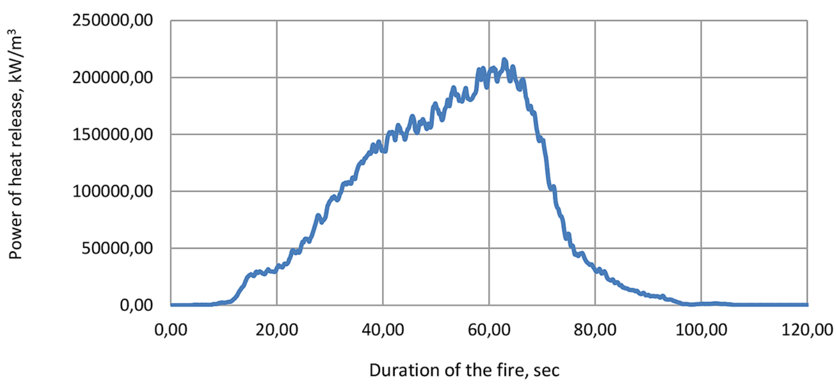

Figure 3. Graphical representation of the power of heat release dependence on the duration of the fire

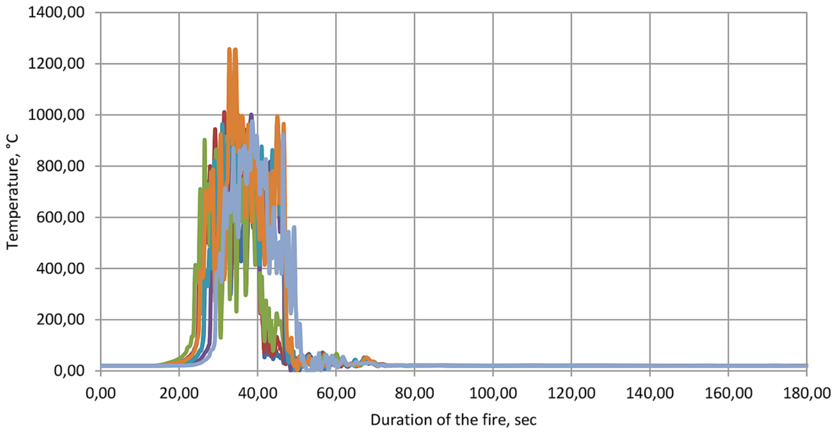

Figure 4. Graphic display of the change in flame temperature in the burning zone depending on the duration of the fire

of pyrogenic succession species is described according to two scales – Drude and Braun-Blanquet (Honcharenko et al., 2003) (Table 2).

The genera *Galium,* and *Erigeron* were represented by 2 species, which was a share of 17%, the rest of the genera – 8% (Fig. 5). Note that the dominant genera are: *Galium* are annual or perennial herbs, sometimes slightly bushy at the base, with erect, decumbent or twisted 4-angled stems, glabrous to tightly pubescent, and sometimes with small spines; *Erigeron* is a genus of annual and perennial branched plants from the aster family.

Table 1. Biological classification of the pyrogenic succession of meadow vegetation of the Ukrainian Roztochchia

Species	Genus	Family
Leucanthemum vulgare Lam.	*Leucanthemum*	*Asteraceae*
Elymus repens L.	*Elymus*	*Poaceae*
Anagallis arvensis L.	*Anagallis*	*Primulaceae*
Sonchus oleraceus L.	*Sonchus*	*Asteraceae*
Galium humifusum M.Bieb.	*Galium*	*Rubiaceae*
Erigeron annuus (L.) Pers.	*Erigeron*	*Asteraceae*
Erigeron acris L.	*Erigeron*	*Asteraceae*
Galium odoratum (L.) Scop.	*Galium*	*Rubiaceae*
Daucus carota L.	*Daucus*	*Apiaceae*
Achillea millefolium L.	*Achillea*	*Asteraceae*
Bellis perennis L.	*Bellis*	*Asteraceae*
Taraxacum officinale (L.) Weber ex F.H. Wigg.	*Taraxacum*	*Asteraceae*

Table 2. Abundance of species of pyrogenic succession of meadow vegetation of Ukrainian Roztochchia

Species	Drude scale	Braun-Blanquet scale
Leucanthemum vulgare Lam.	*Sp*	*1*
Elymus repens L.	Cop_1	*2*
Anagallis arvensis L.	*Sp*	*1*
Sonchus oleraceus L.	*Sp*	*1*
Galium humifusum M.Bieb.	*Sp*	*1*
Erigeron annuus (L.) Pers.	*Sol*	+
Erigeron acris L.	*Sol*	+
Galium odoratum (L.) Scop.	*Sp*	*1*
Daucus carota L.	*Sol*	+
Achillea millefolium L.	*Sol*	+
Bellis perennis L.	Cop_1	*2*
Taraxacum officinale (L.) Weber ex F.H. Wigg.	Cop_1	*2*

The pyrogenic succession in the studied area is represented by only 5 families. The largest representatives are *Asteraceae* – 7 species (59%) and *Rubiaceae* – 2 species (17%). The rest – *Poaceae, Primulaceae, Apiaceae* – are presented by 1 species each (8%) (Fig. 6).

The predominance of *Asteraceae* in the succession is a rather positive phenomenon because they are the most widespread family of the Ukrainian flora and having great practical applications, are used as medicinal, food, fodder, honey, oil, and decorative species. Some members of the *Asteraceae* family can be dangerous or poisonous (helenium, Senecio, *Ageratina altissima*) for humans. The most famous is ragweed, or rather its pollen, which, entering the respiratory tract, causes allergies. The *Asteraceae* family is characterized by lower flammability than *Poaceae*, which is represented by one species in the pyrogenic succession.

CONCLUSIONS

In this work, an investigation of fire in a natural ecosystem was carried out. Taking into account the initial conditions, environmental parameters, and physicochemical characteristics of the combustible material, it was established that the fire of grass and grass stacks lasted more than 60 s, regardless of the specified simulation time – 180 s. The WFDS software environment provided the

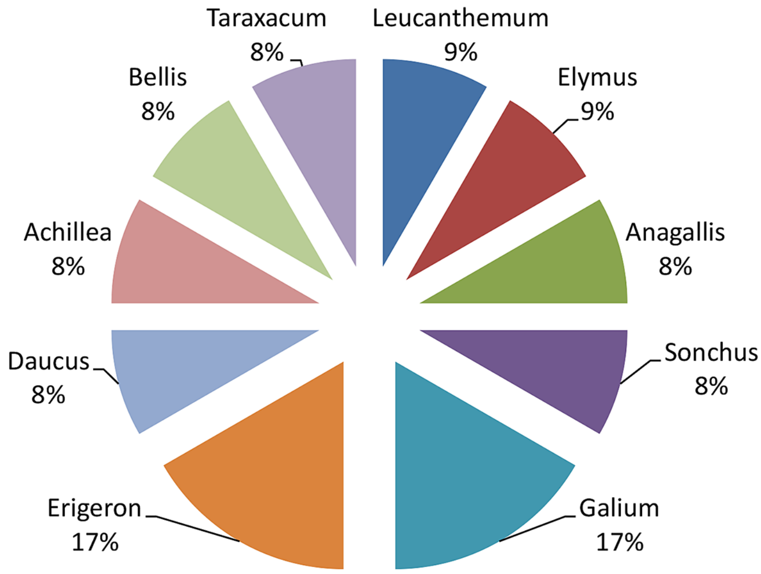

Figure 5. Classification of the pyrogenic succession of the Ukrainian Roztochchia by genera

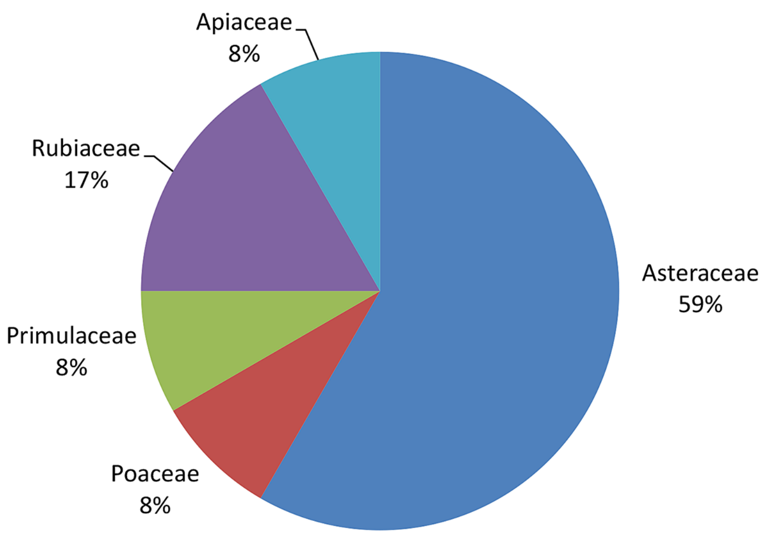

Figure 6. Classification of the pyrogenic succession of the Ukrainian Roztochchia by families

ability to set some fire danger parameters, including flame temperature and power of heat release from fire. It was established that the maximum flame temperature was more than 1250 °C, which was observed for 33 s within the limits of burning grass stacks. However, from the 66th second, a decrease in the flame temperature in the combustion environment of the experimental area to the ambient temperature was observed.

The pyrogenic succession in the studied area is impoverished and is represented by only 5 families. The largest representative in the pyrogenic succession is *Asteraceae* – 7 species (59%) and *Rubiaceae* – 2 species (17%). The rest – *Poaceae, Primulaceae, Apiaceae* – are represented by 1 species each (8%).

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