Application of a three-dimensional model to assess the effect of clear-cutting on carbon dioxide exchange at the soil-vegetation-atmosphere interface

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Abstract. A three-dimensional hydrodynamic model was applied to derive the spatial patterns of the air flows and CO2 fluxes within and around a recently clear-cut area. Results of modeling experiments show a strong influence of the clear-cut on the spatial air flow and vertical and horizontal CO2 flux patterns. The CO2 fluxes at the soil surface, within and above a forest canopy varied significantly depending on weather conditions, prevailed wind direction and influenced by the geometry and size of the forest clearing, tree density and the distance from the forest edges. The rates of horizontal CO2 exchange near the ground surface especially within the downwind forest area and at the leeward forest edge were relatively large and comparable with vertical CO2 fluxes.

1. Introduction
Atmospheric fluxes of green house gases (GHG) such as carbon dioxide (CO2), methane, water vapor etc. between forest ecosystems and the atmosphere are governed by numerous abiotic and biotic factors including key atmospheric parameters, biophysical vegetation and soil properties [1-4]. Any natural and anthropogenic disturbances of forest cover, such as clear-cutting or windthrow damages, can influence surface albedo, net radiation, surface evapotranspiration, CO2 fluxes between land surface and the atmosphere, and can therefore affect local and regional climate conditions [5,6].

Effects of clear-cutting as a widespread logging practice on GHG exchange nowadays are key topics of numerous experimental and modeling studies [7-12]. The eddy covariance and eddy accumulation methods are most widely used techniques for flux measurements in the areas. Mosaic vegetation structure, limited fetch and complex topography make however their wide applications at such experimental sites not reliable due to existed limitations of the methods e.g. required stationary turbulent field around the flux tower, zero horizontal flux divergence, etc.. To derive atmospheric fluxes in such non-uniform areas the two and three-dimensional process-based models look very promising [13-16].

The main goal of the study is to estimate the possible effects of clear-cutting on the air flow disturbances within the atmospheric surface layer as well as to describe the spatial patterns of vertical
and horizontal CO$_2$ fluxes within and around the clear-cut area using a process-based three-dimensional hydrodynamic model for momentum, energy and CO$_2$ exchange.

2. Experimental site and model description

2.1. Experimental site

The clear-cut selected for the study is situated in the area of rational environmental management of the Central Forest State Nature Biosphere reserve (Tver region, Nelinovsky district, 56°26’ N, 33°03’ E) (figure 1). The clear-cut has the area of about 4.5 ha and it is surrounded by mixed spruce forest stand with admixture of birch and aspen trees. The height of the forest stand is about 20 m and the leaf area index (LAI) is about 4 m$^2$ m$^{-2}$. Umbric Albeluvisols are the predominant soils in the area [17]. Amount of organic carbon in the upper 10-cm soil layer varies from 2.7 to 5.8% [12].

![Figure 1](image)

*Figure 1.* Geographical location of the study region, and the aerial image and panoramic photo of the clear-cut area.

2.2. Model description

A developed three-dimensional hydrodynamic model is based on solution of the Navier-Stokes and continuity equations for the wind speed components using the 1.5-order closure scheme [13]. The GHG exchange between soil, vegetation and the atmosphere is described in the model using the so-called reaction - advection - diffusion equation. In the model the 3D wind speed components, $\vec{V} = \{u, v, w\}$, and concentration of CO$_2$, $c$, are considered as functions of two horizontal coordinates ($x$ and $y$), vertical coordinate $z$ and time $t$. To write the equation describing the time average of the differential balance of mass, momentum, and energy we used the Reynolds decomposition between mean and fluctuating wind speed and concentration of CO$_2$. Using Reynolds decomposition the wind speed and concentration of CO$_2$ at a certain time can be expressed as

$$\vec{V} = \bar{V} + \tilde{V}, \quad c = \bar{c} + \tilde{c},$$

where $\bar{V}$ and $\bar{c}$ are the mean values, $\tilde{V}$ and $\tilde{c}$ are the fluctuating components.
where $\overline{V} = \{\overline{u}, \overline{v}, \overline{w}\}$ and $\overline{e}$ are mean values of corresponding parameters, $\overline{V}' = \{u', v', w'\}$ and $e'$ are their deviations.

In case of neutral thermal stratification of the atmospheric boundary layer the Reynolds-averaged Navier-Stokes equation and continuity equation can be written in the following form [18]:

$$
\frac{\partial \overline{V}}{\partial t} + (\overline{V}, \nabla) \overline{V} = -\frac{1}{\rho_0} \nabla \delta P - \left( \frac{\partial}{\partial x} u' \overline{V}' + \frac{\partial}{\partial y} v' \overline{V}' + \frac{\partial}{\partial z} w' \overline{V}' \right) + \overline{F}_{\text{corr}} + \overline{F}^d,
$$

$$\text{div} \overline{V} = 0,$$

where $\rho_0$ is the density of dry air, $\delta P$ is the mean pressure deviation from the hydrostatic distribution, $\overline{F}_{\text{corr}}$ and $\overline{F}^d$ are the Coriolis and drag forces acting within the plant canopy.

The 1.5-closure scheme assumes that the turbulent fluxes can be expressed by gradients of the corresponding mean functions [13,16-19]:

$$
\overline{u'u'} = \frac{2}{3} E - 2K \frac{\partial \overline{u}}{\partial x}, \quad \overline{v'v'} = \frac{2}{3} E - 2K \frac{\partial \overline{v}}{\partial y}, \quad \overline{w'w'} = \frac{2}{3} E - 2K \frac{\partial \overline{w}}{\partial z},
$$

$$
\overline{u'w'} = -K \left( \frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{w}}{\partial x} \right), \quad \overline{u'v'} = -K \left( \frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial x} \right), \quad \overline{v'w'} = -K \left( \frac{\partial \overline{v}}{\partial z} + \frac{\partial \overline{w}}{\partial y} \right),
$$

where $E$ is the turbulent kinetic energy and $K$ is the eddy viscosity. The turbulent kinetic energy and eddy viscosity can be expressed according to Wyngaard [18] as

$$
E = \frac{1}{2} \left( \overline{u'}^2 + \overline{v'}^2 + \overline{w'}^2 \right), \quad K = C_\mu \frac{E^2}{\overline{e}},
$$

where $C_\mu$ is a dimensionless model parameter, and $\overline{e}$ is the dissipation rate for $E$. Turbulent kinetic energy and the rate of its dissipation can be found from the following system of differential equations [13, 15, 16, 20]:

$$
\frac{\partial E}{\partial t} + (\overline{V}, \nabla) E = \text{div} \left( \frac{K}{\sigma_E} \nabla E \right) + P_E - \overline{e}, \quad \sigma_E = \sigma_\varphi = 2,
$$

$$
\frac{\partial \varphi}{\partial t} + (\overline{V}, \nabla) \varphi = \text{div} \left( \frac{K}{\sigma_\varphi} \nabla \varphi \right) + \varphi \left( \frac{C_{\varphi_1}}{E} \cdot P_E - C_{\varphi_2} \cdot \overline{e} \right) + \Delta_\varphi, \quad \varphi = \frac{\overline{e}}{E}, \quad C_{\varphi_1} = 0.52, \quad C_{\varphi_2} = 0.8.
$$

The shear production of turbulent kinetic energy, $P_E$, can be expressed as:

$$
P_E = -\left[ \overline{u'v'} \frac{\partial \overline{u}}{\partial x} + \overline{u'w'} \frac{\partial \overline{u}}{\partial y} + \overline{w'w'} \frac{\partial \overline{u}}{\partial z} + \overline{v'u'} \frac{\partial \overline{v}}{\partial x} + \overline{v'v'} \frac{\partial \overline{v}}{\partial y} + \overline{v'w'} \frac{\partial \overline{v}}{\partial z} + \overline{w'u'} \frac{\partial \overline{w}}{\partial x} + \overline{w'v'} \frac{\partial \overline{w}}{\partial y} + \overline{w'w'} \frac{\partial \overline{w}}{\partial z} \right].
$$

The term $\Delta_\varphi$ describes the energy dissipation increase within the vegetation cover [13] and can be written as

$$
\Delta_\varphi = 12 \sqrt{C_\mu \cdot (C_{\varphi_2} - C_{\varphi_1})} \cdot c_d \cdot LAD \cdot \overline{|V|} \cdot \sigma_\varphi,
$$

where the function $LAD = LAD(x, y, z)$ is the leaf area density, $\text{m}^2\text{m}^{-3}$, and $c_d$ is the dimensionless drag coefficient.

To describe a 3D pattern of the mean CO$_2$ concentration, $\overline{c}$, the reaction - advection - diffusion equation is applied. It can be written in the following general form

$$
\frac{\partial \overline{c}}{\partial t} + (\overline{V}, \nabla) \overline{c} = \text{div}(K_c \nabla \overline{c}) + F_c.
$$
The turbulent exchange coefficient $K_c$ is assumed to be proportional to the eddy viscosity, $K$, and it is equal to $K_c = Sc^{-1}K$, where $Sc$ is the Schmidt number ($Sc=0.75$ in our modeling study) [19]. The term $F_s$ describes the sources and sinks of CO$_2$ within the plant canopy and at the soil surface.

Plant canopy photosynthesis and respiration rates are calculated using an aggregated approach based on a model suggested by Ball et al. [21] and modified by Leuning [22], on the Beer-Lambert equation for solar radiation penetration within a plant canopy [23], and on the algorithm describing the response of leaf stomatal conductance to incoming photosynthetically active solar radiation [24]. The dependence of soil CO$_2$ emission on soil temperature is described using the Arrhenius equation [25].

The 3D wind and CO$_2$ flux distributions were simulated for a modeling domain of about 0.25 km$^2$, covering entire clear-cut area and the large part of surrounding forest. To quantify the initial vertical distribution of wind speed above the forest canopy within the modeling domain we used the well-known logarithmic wind profile. The vertical wind profile at the upwind lateral boundary of the modeling domain was derived using the one-dimensional hydrodynamic model considering the vertical LAI distribution of the upwind forest stand [26]. For other lateral boundaries the zero-flow conditions for all required functions, i.e. wind speed components, turbulent kinetic energy, function $\phi$ and pressure deviation $\partial\phi$, were implemented.

The developed model was validated using field measurements of the energy and CO$_2$ fluxes obtained for the selected clear-cut area using the eddy-covariance technique in 2016 [11]. Results showed a plausible agreement between measured and modeled fluxes under various environmental conditions.

2.3. Scenarios of modeling experiments
To describe the possible effects of clear-cutting on the air flows and CO$_2$ fluxes at selected experimental site the prevailed south wind direction in the study area in summer was considered. For modeling experiments we selected a reference sunny summer day with the air temperature at noon close to 25°C, soil temperature at 10 cm depth of 20°C, and soil moisture content equal to 70% of field capacity. The horizontal homogeneity of soil temperature and moisture distribution within the clear-cut and surrounding forest was assumed. The mean wind speed at 100 m above the ground was taken to be equal to 10 m s$^{-1}$. The neutral thermal stratification within the atmospheric surface layer was also assumed.

3. Results and discussion
The results of modeling experiments demonstrated a significant influence of vegetation heterogeneity on the spatial air flow patterns under selected weather conditions both within and around the clear-cut area (figure 2). The wind speed near the ground surface (taken at a height of 4 m above the ground) reached maximum values (up to 3.5 m s$^{-1}$) at windward edge of the clear-cut area, whereas the minimum wind speeds (less than 0.4 m s$^{-1}$) were obtained at the leeward clear-cut part. The wind speed pattern at the forest floor within the surrounding forest is characterized by large heterogeneity and it varied between 0.4 and 3.0 m s$^{-1}$ in downwind (northern) part of the surrounding forest, and between 0.6 and 1.0 m s$^{-1}$ in upwind (southern) forest part. Because of a very complex shape of the clear-cut boundary (figure 1) the wind directions near the ground surface at various locations within the modeling domain differed significantly from the selected prevailed wind direction near the upper boundary of the atmospheric surface layer (assumed to be equal 100 m).

The spatial patterns of vertical wind component near the ground surface are also characterized by significant horizontal heterogeneity - the sites with upward air flows alter with sites where the downward air movements were prevailed. Such complex mosaic of wind fields is most pronounced at the leeward forest edge of the clear-cut area (figure 2). The air stream flowing over leeward edge of the forest stand goes down and initiates both the forward and backward air flows near the ground as well as the upward air flows close to leeward forest edge.

The northern part of the clear-cut area situated close to windward forest edge is characterized by well pronounced upward air flows. The similar wind distributions after air flow interaction with forest clearing and openings of different sizes were reported in the modeling and experimental studies provided
by Frank and Ruck [27] and Levashova et al [28]. These studies reported, inter alia, a large impact of the clearing width on the air flow field above and within the downstream forest area.

The spatial patterns of horizontal and vertical wind components simulated by the three-dimensional model for the middle and upper parts of forest canopy are less heterogeneous. The wind directions tend slowly to coincidence with prevailed wind direction above the forest canopy as the height above the ground is increased. However the downward and upward air flows at leeward and windward clear-cut parts remain well pronounced within both the entire forest canopy and the lowest part of the atmospheric surface layer.

![Simulated vertical and horizontal wind components](image)

**Figure 2.** Simulated vertical, \( w \) (upper panel) and horizontal, \( \vec{V} = \{u, v\} \) (lower panel) wind components within and around the clear-cut area at 4, 12, 20 m above the ground surface. Black line shows the boundary of the clear-cut area.

The obtained highly non-uniform spatial distribution of the air-flows combined with mosaic soil CO\(_2\) emission, and tree and herbaceous plant photosynthesis and respiration rates within and around the clear-cut area [29] result in a very heterogeneous distributions of atmospheric CO\(_2\) fluxes at different heights above the ground within and above the forest canopy (figure 3). The leeward (southern) part of the clear-cut area and adjacent part of the forest are characterized by maximum horizontal gradients of vertical CO\(_2\) fluxes. The vertical CO\(_2\) fluxes at the site at a height of 4 m above the ground ranged from -12 µmol m\(^{-2}\) s\(^{-1}\) (CO\(_2\) uptake) to +14 µmol m\(^{-2}\) s\(^{-1}\) (CO\(_2\) release). Such very high upward CO\(_2\) fluxes may result from horizontal advection of the CO\(_2\) enriched air from the upwind forest understory.
The maximum upward CO$_2$ fluxes are also obtained at the forest edge in the western part of the clear-cut area and they were comparable with the horizontal CO$_2$ fluxes (figure 3). One of the possible reasons for such anomalies is a very intensive horizontal CO$_2$ exchange within the forest canopy air space obtained in the western and northwestern parts of forest canopy adjacent to the clear-cut area (figures 2-3). Moreover, the spatial CO$_2$ flux pattern is also influenced by very complex geometry of the clear-cut boundary.

The analysis of the spatial patterns of horizontal CO$_2$ fluxes at the height of 4 m above the ground revealed that the maximum horizontal CO$_2$ flow rates occurred at leeward clear-cut edge and in the northwestern (downwind) part of the forest stand adjacent to the clear-cut area (figure 3, lower panel). Whereas the vertical CO$_2$ fluxes within the forest canopy air space in the northwestern part of the modeling domain varied from -3 to +4 µmol m$^{-2}$ s$^{-1}$, horizontal CO$_2$ fluxes in this place reached +10 - +12 µmol m$^{-2}$ s$^{-1}$. Such difference can be explained by rather low vertical turbulent exchange within the relatively dense forest canopy (LAI > 4.0 m$^2$ m$^{-2}$). A relatively sparse understorey promotes a rather free horizontal CO$_2$ exchange within the forest canopy air space. Similar relatively low vertical CO$_2$ exchange was also obtained for upwind forest sites situated at some distance from the forest edge.

![Simulated vertical and horizontal CO$_2$ fluxes within and around the clear-cut area at 4, 12, 20 m above the ground surface. Black line shows the boundary of the clear-cut area.](image)

**Figure 3.** Simulated vertical and horizontal CO$_2$ fluxes within and around the clear-cut area at 4, 12, 20 m above the ground surface. Black line shows the boundary of the clear-cut area.

Model estimations of atmospheric CO$_2$ fluxes within tree crowns and above the forest canopy, show, on the one hand, sharp increase of the canopy CO$_2$ uptake due to high photosynthetic rate of tree foliage and, on the other hand, gradual decrease of the horizontal CO$_2$ exchange rates (figure 3). Such trends
can be explained by both smaller horizontal gradients of CO\textsubscript{2} concentrations at these levels and greater contribution of forest trees into the total atmospheric CO\textsubscript{2} fluxes.

The obtained extremely high heterogeneity of momentum and CO\textsubscript{2} fluxes within and around the clear-cut area raises the issues of possible uncertainties of flux estimations over non-uniform areas by the widely used micro-meteorological methods for flux measurements such as eddy covariance or eddy accumulation techniques. As it was already mentioned above, these methods are based on numerous assumptions (e.g. negligible air flow convergence and divergence, insignificant density fluctuations, etc.) and assume the horizontal terrain (vegetation and topography) homogeneity [30]. In case of a non-uniform terrain the accurate flux measurements require complete air flow re-establishing after its interaction with any obstacle (e.g. topographic obstacles, forest edges, etc.) in the direction upwind from the point of flux measurements. The air flow can be classified as re-established if the derivatives of some key air flow parameters, i.e. horizontal and vertical wind speed components, turbulent kinetic energy, turbulent coefficient, etc., regarding to both horizontal coordinates will tend to zero. An analysis of the spatial wind and flux patterns within our clear-cut area for corresponding meteorological conditions (air temperature, solar radiation, wind speed and direction) shows at least three sites that are characterized by almost re-established air flows (a zero vertical wind velocity is used as a criteria of re-established air flow), minimal horizontal divergence of CO\textsubscript{2} fluxes and, therefore, can be suitable for representative flux measurements: the northern (windward) part of the clear-cut area near the ground surface (<4 m) and two sites within down- and upwind parts of the surrounding forest at a minimum distance of 100-150 m from the clear-cut boundary. Any flux measurements performed at other parts of the clear-cut and surrounding forest as well as within and above tree crowns due to very high contribution of horizontal advection terms can result in large uncertainties of flux estimations using eddy covariance or eddy accumulation techniques.

It should be emphasized that provided numerical experiments show only an example of possible effects of surface heterogeneity on the air flows and CO\textsubscript{2} fluxes within the atmospheric surface layer. It can be expected that the air flow and flux responses can be quite different in case of other shapes and sizes of the clear-cut area, and under different environmental conditions.

4. Conclusion
The results of numerical experiments obtained with the newly developed three-dimensional hydrodynamic model show a forceful influence of clear-cutting on momentum and CO\textsubscript{2} exchange at the soil - vegetation - atmosphere interface. Air flow deformations at the forest edge result in very non-uniform wind distribution within both the clear-cut area and surrounding forest. These air flow disturbances are also traced in horizontal wind distributions within the atmospheric surface layer above the forest canopy. Air flow deformation also results in changes of the CO\textsubscript{2} fluxes within both the forest canopy and the atmospheric surface layer. Maximum changes of the vertical and horizontal CO\textsubscript{2} fluxes near the ground surface (at 4 m above the ground) are predicted at windward and leeward clear-cut edges. The horizontal CO\textsubscript{2} fluxes at the forest floor at downwind (northern) forest part are slightly greater than the vertical CO\textsubscript{2} fluxes. A rather small vertical CO\textsubscript{2} exchange within the air space of forest canopy surrounding the clear-cut area can be explained by relatively dense forest canopy inhibiting exchange process between forest canopy air space and the atmospheric surface layer.

A very high heterogeneity of the air flows and CO\textsubscript{2} fluxes within and around the clear-cut area is obviously governed by numerous factors, including atmospheric conditions, structure and biophysical properties of vegetation and soil. To explain the principal mechanisms of CO\textsubscript{2} (as well as another GHG) flux variations at the "soil - vegetation - atmosphere" interface in details new multifaceted experimental and modeling studies in various experimental sites and under a broader spectrum of environmental conditions are obviously required. They can help to answer still open research questions, such as adequate extrapolation (up-scaling) of local (point) measurements of any GHG fluxes at non-uniform landscapes to ecosystem and regional scales and to estimate possible errors of flux measurements provided using e.g. eddy covariance or eddy accumulation methods over non-uniform land surfaces with complex topography and mosaic vegetation.
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