Biomass residues adjacent forest roads in two different forest species (Fagus sylvatica and Pinus brutia): quantities and evaluation of their biogas production potential

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Abstract. In this study the quantity of biomass residues accumulated at a low-altitude Mediterranean forest (pinus and fagus clusters) were evaluated under field conditions. Samples of fresh and dry leaves (litter) were digested in batch anaerobic reactors to evaluate their biogas production potential. The quantity of pine needles and fagus leaves accumulated onto the forest carpet was on average 670 and 1440 g/m², respectively and they were characterized by a low moisture content (10-11%). The biogas production potential was 100 and 150 L/kg volatile solids for pinus and fagus litter respectively (compared to 140 and 300 L/kg VS for the fresh pine needles and fagus leaves). The data from both field and laboratory studies were used to calculate the biogas yield per km of forest road, if the collected biomass is disposed of to an anaerobic digestion facility. The conceptual model applied revealed that it is possible to recover up to 500 and 1000 m³ CH₄ / km, from the pinus and fagus clusters respectively. Concluding, pine needles and fagus leaves are important resources and can be efficiently used for energy production in anaerobic digestion facilities.

1. Introduction
Biomass as a fuel plays an important role in addressing energy demands [1]. Biomass-based energy production has significant social and economic implications for agricultural and mountainous areas and can contribute to the reduction greenhouse gas emission [2]. Moreover, energy autarky and minimization on the dependency of imported fossil fuels is of major concern [3]. Forest residues such as tree branches and leaves, small trees, wood processing residues (i.e. sawdust, wood chips), bushes/shrubs (i.e. low vegetation biomass) are sources of biomass that remain largely unexplored, especially considering the production of biogas. In order to increase the production efficiency and provide access to biomass resources, there is an urgent need for new and improved road networks [4]. The latter maximize the efficiency of all forestry activities, minimize costs and environmental consequences [5]. Road networks can additionally contribute to the prevention of forest fires by regular harvesting of forest biomass. These resources needs to be valorized rather than disposed.
Biogas production at the European Union is based primarily on agricultural and agro-industrial residues/wastes and corresponds to 18 bil CH4 per year [6]. According to the EU Methane Strategy, the consumption of biogases (biogas and biomethane) is expected to grow from 18 Mtoe (2020) to 54-72 Mtoe by 2050. This increase (3 to 4 fold) requires that new sources of biomass are valorized in anaerobic digestion facilities [7]. Forest residues have received significant attention for biogas production during the last 15 years (as demonstrated by the increasing number of publications). They consist mainly of cellulose, hemicellulose, lignin, extractives and inorganic material, while the complex structure of lignocellulose often results in low biodegradability and biogas yield values [8]. Matsakas et al [8] reviewed biogas yield values from different softwoods (spruce, pine, cedar and other) and hardwoods (birch, willow, eucalyptus, poplar and other) and concluded that forest material pretreatment is necessary before use in anaerobic digestion facilities. Different types of pretreatment involve physical (size reduction, thermal processing), chemical (e.g. alkaline) and biological processes (e.g. enzymatic).

Aim of this study was to evaluate the quantity of pine needles and fagus leaves accumulated onto the forest carpet (litter) and calculate their biogas production potential using laboratory-scale anaerobic digesters. A conceptual model was also developed to calculate the methane yield per km forest road in case that the litter is disposed of to an anaerobic digestion facility.

2. Materials and Methods

2.1. Field studies
The study was conducted at North Greece (Flamouri forest) at a low-altitude Mediterranean Pinus (40.909297° N, 23.343382° E) and Fagus forest (40.829084° N, 23.348551° E) (see Figure 1). Site visits were performed during the summer season (May - June 2020) to quantify the amount of leaf/needle (litter) accumulated onto the forest carpet (see Supplementary Material). For this purpose litter was removed from an area of 1 m² and weighted while samples were transported to the laboratory for further characterization. The pinus cluster consisted of pinus brutia trees aged 50 to 60 years from reforestation activities. The tree height ranged from 15 to 20 m and the distance between trees was 3 to 5 m. The fagus trees had an average trunk diameter between 0.5 to 0.8 m. The fagus tree height was 20 to 25 m and a distance between 2 to 3 m.

2.2. Laboratory studies
Samples of fresh leaves/needles and litter were digested in batch anaerobic reactors [9]. The samples were initially grinded before use. The anaerobic reactors had a working volume of 150 mL and were operated at mesophilic conditions (39 °C). The reactors were inoculated with anaerobic sludge from a full-scale anaerobic digestion facility treating dairy manure and maize silage. The composition of the inoculum was: total solids = 35 g/L, volatile solids = 22 g/L, pH = 7.82, electrical conductivity = 25 mS/cm, PO₄-P = 83 mg/L, NH₄-N = 2400 mg/L. Each anaerobic reactor was loaded with 150 mL of inoculum and 0.45 g VS substrate, corresponding to a substrate to inoculum ratio of 0.14 (VS basis). Each sample was digested in duplicate and the reactors were flushed with nitrogen for 3 mins to remove oxygen from the headspace.

2.3. Analytical methods
Biomass samples were characterized in terms of their moisture, total solids (TS) and volatile solids (VS) content according to the Standard Methods [10]. The biogas production during the anaerobic digestion experiments was recorded using an inverse column filled with acidified water. Biogas methane content was determined using an infrared biogas analyzer (BINOS-Leybold GmbH, Germany).
3. Results and discussion

3.1. Quantity and biogas production of needles / leaf litter
The quantity of pine needles and fagus leaves accumulated adjacent to forest roads was on average 670 (±320) and 1440 (±200) g/m² (Figure 2). Since the measurements were performed during the dry season, the litter from both sites was characterized by a low moisture content between 10-11%. The volatile solids content were equal to 97 and 82 %TS for the pinus and fagus litter respectively.

3.2. Biogas production potential
Batch anaerobic digestion of needles and leaf litter revealed relatively low biogas yield on average 100 and 150 L/kg VS and a methane yield 60 and 90 NL CH₄ / kg VS, respectively. Fresh pine needles and fagus leaves generated significantly higher quantities of biogas (1.4 and 2.0 times higher, respectively). Based on the results of previous studies the methane yield values ranged from 150 NL/kgVS for oak leaves, 130 NL/kgVS for phoenix tree leaf, 80 NL/kgVS for cauliflower leaves, 78 NL/kgVS for grape leaves, 30 NL/kgVS for tomato leaves and 25 NL/kgVS for strawberry leaves [11-14]. These values are within the same range with the results of our work.
Figure 2. Distribution of the quantity of (a) *Pinus* needles and (b) *Fagus* leaves litter accumulated adjacent to forest roads in the study area.

Figure 3. Cumulative biogas yield of fresh and litter (a) *Pinus* needles and (b) *Fagus* leaves.
3.3. Calculation of biogas production per km forest road

The data from both field and laboratory studies were used to calculate the biogas production potential per km of forest road, if the collected biomass is disposed of to an anaerobic digestion facility. The conceptual model applied was based on the assumption that the methane yield per km forest road is linearly related to (a) the quantity of litter accumulated per unit forest area (which is derived from observations and field measurements), (b) the size of litter collection area adjacent to forest roads (which depends on accessibility, topography, etc) and (c) the methane yield coefficient of the accumulated biomass. The proposed model is expressed by the following equation:

\[ Y_{CH4/km} = 1000 \times Y_{CH4/OM} \times OM \times W_{LIT/A} \times d_{LIT/km} \]

where

- \( Y_{CH4/km} \) = methane yield per km forest road (m³/km)
- \( Y_{CH4/OM} \) = methane yield per kg volatile solids (L/kg VS)
- \( OM \) = organic matter content of biomass samples (kg VS/kg fresh matter)
- \( W_{LIT/A} \) = quantity of leaf/needle litter accumulated per unit forest area (kg/m²)
- \( d_{LIT/km} \) = average distance of litter collection adjacent to forest road (m per km road)

Considering the results from the laboratory studies, the methane yield values per kg of volatile solids and the organic matter content of biomass samples were taken as 60 and 90 NL CH₄ / kg VS and 0.75 and 0.87 kg VS/ kg fresh matter, for the *Pinus* and *Fagus* litter respectively. According to Elsayed et al. [15] fallen leaves were characterized by a moisture and volatile solids content equal to 13% and 96%, respectively, and a methane yield coefficient 130 NL/kg VS. In a similar study, fallen oak leaves were characterized by moisture and volatile solids content of 12% and 70%, respectively and yielded methane at 150 NL/kg VS [11].

Figure 4 show the calculated methane yield per km forest road (see equation 1) for the *Pinus* and *Fagus* clusters respectively, considering different length of litter collection area adjacent to forest road and different quantity of litter accumulated onto the forest carpet. Clearly the methane recovered per km forest road is site-specific and may come up to 500 and 1000 m³/km for the *Pinus* and *Fagus* clusters respectively. Considering that biogas is converted to electricity and introduced into the grid it is possible to calculate the maximum income at 400 and 800 €/km forest road for the *Pinus* and *Fagus* clusters respectively (assuming an electrical efficiency of the generator 4 kWh-el / m³ CH₄ and a feed-in-tariff 0.20 € / kWh-el). For an objective assessment however, one should also consider the costs for biomass collection, pre-treatment (grinding), transportation as well as the depreciation and operating costs of the biogas production facility.

4. Conclusions

Biomass harvesting is important for the prevention of forest fires. The generated residues however, need to be valorized rather than disposed. Pine needles and *Fagus* leaves can be efficiently used for biogas production in anaerobic digestion facilities. In this study a conceptual model was developed in order to calculate the methane yield per km of forest road if the collected biomass litter is disposed to an anaerobic digestion facility. The model was based on field (quantity of pine and fagus litter accumulated onto the forest carpet) and laboratory measurements (biogas production potential of the biomass). The results showed that methane yield per km of forest road is site-specific and may come up to 500 and 1000 m³/km for the *Pinus* and *Fagus* clusters respectively. Apart from the prevention of forest fires, this approach can help Mediterranean countries to gain an additional energy source.
Figure 4. Methane yield per km of forest road as a function of litter collection length and the quantity of litter accumulated onto a (a) *Pinus* and (b) *Fagus* forest.

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Supplementary material

**Photo 1.** Representation of the *fagus* forest road and detail of the *fagus* leaf litter.

**Photo 2.** Representation of the *pinus* forest road and detail of the *pinus* leaf litter.